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TRANSMISSION LINE REFURBISHMENT STUDY: TESTS ON KINGSTON TYPE STEEL TRANSMISSION TOWERS - SMITHS FALLS

Report No. 89-79-K

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ABSTRACT

As part of the ongoing transmission line refurbishment study, three single circuit 115 kV, Kingston type suspension towers on rock-anchor foundations were tested to failure. The type of loads applied on the towers were chosen to represent unbalanced loads due to broken skywire and conductor, heavy ice, strong wind and wind-on-ice loads. Selected tower members and foundations were instrumented to measure the member loads, tower deflections and foundation movement during various stages of testing. The measured values were compared with the corresponding predicted values. The correlation is good between the predicted and actual tower failure loads. The tower tests confirmed that there is reserve strength available for upgrading the conductor on this line. The measured tower member loads and foundation loads correlated fairly satisfactorily with the corresponding calculated values. The rock-anchor foundation did not show any movement at all.

job	file	date	report no.
21-127-431	825.15	June 27, 1989	89-79-K

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EXECUTIVE SUMMARY

TRANSMISSION LINE REFURBISHMENT STUDY: TESTS ON KINGSTON TYPE STEEL TRANSMISSION TOWERS - SMITHS FALLS

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Applied Mechanics Section
Mechanical Research Department

A comprehensive program has been initiated by Ontario Hydro to study the condition of the existing older overhead transmission lines. The major objective of this study is to assess the condition and remaining life of conductors, hardware, insulators, structures and foundations.

As part of the ongoing transmission line refurbishment study, three single circuit 115 kV, Kingston type suspension towers on rock-anchor foundations were tested to failure. The type of loads applied on the towers were chosen to represent unbalanced loads due to broken skywire and conductor, heavy ice, strong wind and wind-on-ice loads. Selected tower members and foundations were instrumented to measure the member loads, tower deflections and foundation movement during various stages of testing. The measured values were compared with the corresponding predicted values. The correlation is good between the predicted and actual tower failure loads. The tower tests confirmed that there is reserve strength available for upgrading the conductor on this line. The measured tower member loads and foundation loads correlated fairly satisfactorily with the corresponding calculated values. The rock-anchor foundation did not show any movement at all.

JC

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SUMMARY OF PART I

TESTS AND TEST PROCEDURES

G.A. Senkiw and S.G. Krishnasamy

A total of 3 single circuit, 115 kV, Kingston type suspension towers on rock-anchor foundations were tested to failure. The first two towers were loaded in the following sequence:

- Heavy Ice
- Broken Skywire
- Broken Outer Conductor
- Broken Centre Conductor
- Heavy Ice and Strong Wind (Wind-On-Ice) - the towers were loaded to failure under this loading)

The loading sequence on the third tower was as follows:

- Heavy Ice
- Broken Skywire - the tower prematurely failed under this loading
- Broken Outer Conductor

This part of the report describes in detail the preparation of the test and reaction towers (built for applying the wind-on-ice load), various applied loads and load steps, test procedures and safety procedures. Numerous illustrations are included to describe the various stages of testing, loading arrangements and tower failure modes.

The tests were carried out as planned without any major deviations and all the equipment performed satisfactorily.

SUMMARY OF PART II

INSTRUMENTATION, MEASUREMENTS AND DATA ACQUISITION SYSTEM

S.G. Krishnasamy, C.J. Pon, G.A. Senkiw,
R.W. Wolfendale, and J. Marsala

This part of the report describes the type of measuring instruments used in tower testing, the various measurements done during each tower test and the data acquisition system used to record and store the measured data. The measuring system consisted of load cells, strain gauges, linear potentiometer displacement transducers (LPDT) and a weather instrument package. The data acquisition system consists of data loggers, signal conditioners, microcomputers and a printer.

The following are the measurements made during a typical tower test:

- Strain in selected tower members to calculate member loads
- Loads applied to towers at conductor and skywire attachment points
- Foundation movements
- Displacement of selected tower joints
- Wind speed and direction and temperature at the site

Two data acquisition systems were used to store all the data for further analysis.

The instruments and data acquisition systems were calibrated in the laboratory and re-checked in the field before the tests. The measurement accuracy was within a few percentage points and all the systems performed extremely well.

SUMMARY OF PART III

DATA ANALYSIS AND DISCUSSION

S.G. Krishnasamy, M. Tabatabi, and H.S. Radhakrishna

In this part of the report the information gathered from the tower testing program is presented along with some selected data analysis. Some typical measurements are compared with corresponding predicted values. The following analyses were performed on the data:

- Comparison of predicted and actual tower failure loads
- Comparison of calculated and measured tower deflections
- Study of foundation loads and deflections
- Analysis of load distribution in selected tower members

The correlation is good between the predicted and actual tower failure loads. Considering the assumptions involved in calculating the member loads and the structural and loading asymmetry that existed in the tests, the extent of correlation is satisfactory between the calculated and measured tower member loads. In general the measured member loads were lower than the calculated values and during the tower tests to failure the members were subjected to about 50 percent of their load carrying capacity.

In general the agreement is good between the measured and estimated values of foundation loads and the rock-anchor foundation did not show any movement at all. The tests also show that the towers have reserve strength of about 50 percent of the loads applied in service. This reserve strength can be utilized for upgrading the conductor on this line.

The report provides detailed information on each stage of data analysis along with tables and figures. The data analysis indicates that the method used to analyze the tower structure and the instruments used in the test are quite adequate.

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To Mr. D.E. Horrocks
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TRANSMISSION LINE REFURBISHMENT STUDY:
TESTS ON KINGSTON TYPE STEEL
TRANSMISSION TOWERS - SMITHS FALLS

S.G. Krishnasamy
Applied Mechanics Section
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INTRODUCTION

Since Ontario Hydro's oldest overhead transmission lines are approaching their 80th year, it is clear that a large scale program must be in place to either rebuild or refurbish these older transmission lines. In order to assess the condition of these existing older lines and determine their useful remaining life, Ontario Hydro has approved a definition phase of the Transmission Line Refurbishment Study. The major objective of this definition phase is the assessment of the condition and remaining life of conductors, hardware, insulators, structures and foundations. This report will focus on the assessment of the strength and condition of some of the older steel towers and their footings.

In late September 1987, a working group consisting of personnel from Research Division, Design & Development Division - Transmission, Construction and Services Division, System Planning Division and Transmission Operations Division was formed to plan and carry out the assessment of the condition and remaining life of the older transmission lines. In November 1987 two sites were selected to conduct full-scale tests on existing 115kV, Kingston type suspension towers which became surplus on account of relocating the S1K circuit between Smiths Falls and Kingston, Ontario. However, in early 1988, due to a variety of reasons, the test site, consisting of three towers located at Hinchinbrooke Crossing, approximately 20 km south of Smiths Falls, Ontario (Figure 1), was selected.

This report consists of three parts and describes in detail the following aspects of the study:

- Tests and Test Procedures (Part I)
- Instrumentation, Measurements and Data Acquisition System (Part II)
- Data Analysis and Discussion (Part III)

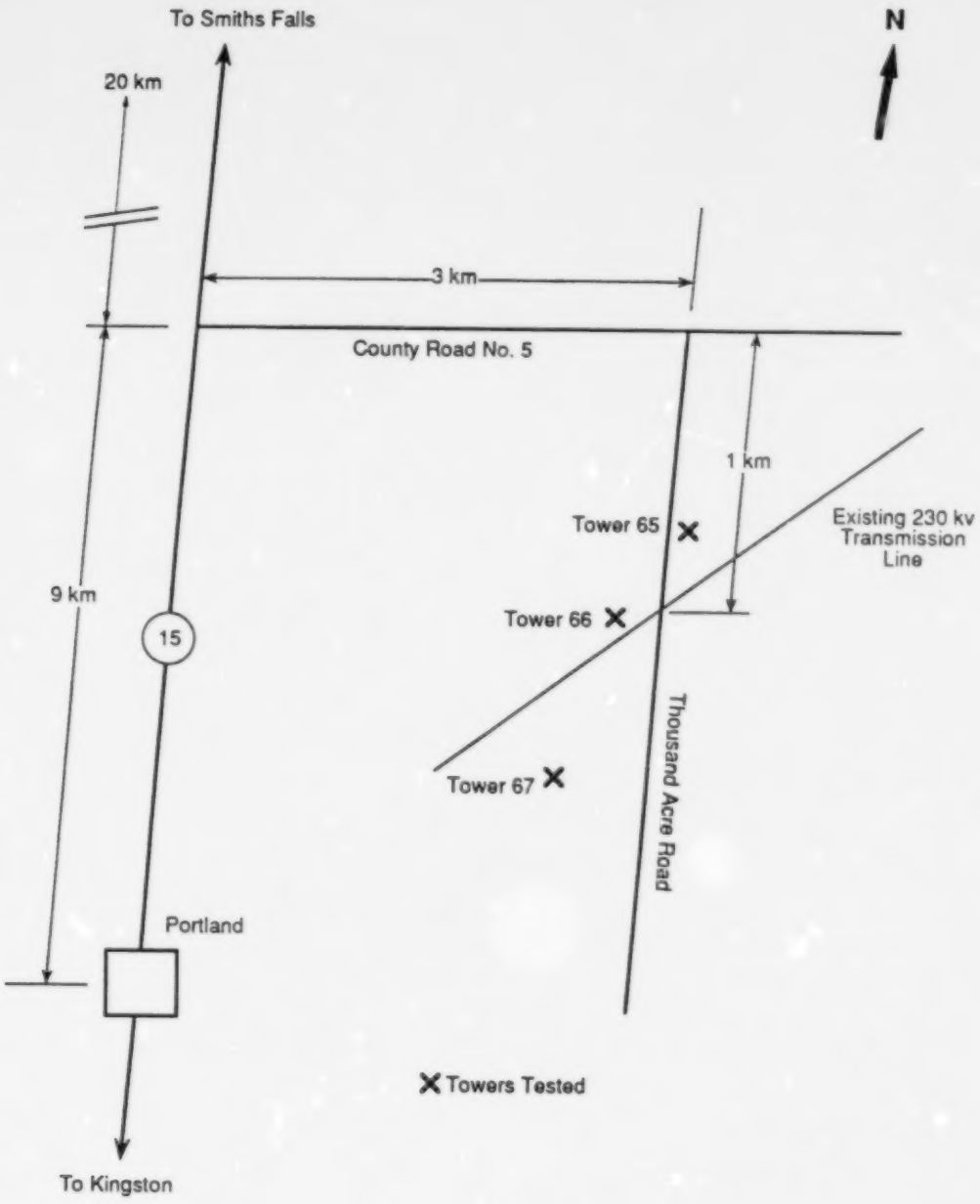


FIGURE 1

LOCATION OF TOWER TEST SITE NEAR SMITHS FALLS, ONTARIO

PART I

TESTS AND TEST PROCEDURES

G.A. SENKIW AND S.G. KRISHNASAMY

PART I

TESTS AND TEST PROCEDURES

1.0 DESCRIPTION OF THE TEST TOWERS

The dimensions, conductor and span details as well as the loads for the single circuit, 115 kV, Kingston type suspension tower are given in Figure 1. Two typical views of the Kingston type towers are given in Figure 2. These towers were built in 1928. Most of the connections are made by bolting the steel angles together but at some joints steel tie plates were used. Tensile tests on selected tower members showed that the yield and ultimate strength of the steel used were 44×10^3 psi and 60×10^3 psi respectively. Towers 66 and 67 were of regular height while Tower 65 had a 10 ft extension at the base.

2.0 DESCRIPTION OF TOWER TESTS & TEST SCHEDULE

In discussions with Transmission Line Design the following tower tests and order of testing were established:

2.1 Test A: Heavy Ice

This test represents the heavy ice loading on the tower. The loading steps, Table I, are based on the vertical downward loads presented in Load Combination C, in Figure 1, except that the load at point 6 was added onto point 2.

2.2 Test D1: Broken Skywire

This test simulates the unbalanced load imposed on the tower due to a broken skywire at point 2, in Figure 1. This along-the-line load is based on Load Combination B with IIIc in Figure 1. The incremental load steps applied are given in Table II.

2.3 Test D2: Broken Outside Conductor

Test D2 simulates the unbalanced load imposed on the tower when one of the outside conductors (point 5 in Figure 1) fail. This along-the-line load is described in Load Combination B with IIIb in Figure 1. Table III lists the applied load steps.

2.4 Test D3: Broken Centre Conductor

Test D3 represents the load (point 4 in Figure 1) on the tower when the centre conductor fails. This along-the-line load is given in Load Combination B with IIIa in Figure 1. Table IV lists the applied load steps.

2.5 Test B: High Wind & Ice Load (or Wind-on-Ice Load)

This test represents the transverse load on the tower caused by high winds on ice-covered conductors (called hereafter wind-on-ice loads) which acts normal to the line. This test would lead to the tower failure as predicted from analysis. The applied load steps are given in Table V. This loading condition is based on Load Combination A in Figure 1.

2.6 Applied Tower Loads

Load cells of different capacities were used to monitor the load applied to each tower. Four 5-kip capacity load cells were used to measure the applied vertical loads while a 15 kip capacity load cell was used to monitor the applied along-the-line loads. An angle indicator was mounted on a load cell frame to record the angle of the along-the-line load with respect to the horizontal during Tests D1, D2 and D3. Four 10-kip load cells were used to monitor the transverse load.

2.7 Test Schedule

The schedule for the preparation and execution of the tests is given in Table VI.

3.0 INSPECTION OF TOWERS & FOOTINGS

3.1 Towers

Prior to preparing the towers for testing, each tower was closely inspected for damaged steel members and missing bolts. The crew was instructed to replace any damaged members or missing bolts.

3.2 Tower Footings

An inspection of the tower footings revealed that they consisted of a pair of grouted rock anchors with a small steel and concrete pad which sat on top of the bedrock, Figure 3.

Towers 65,66 and 67 were anchored to bedrock under a shallow overburden of 1 to 2 feet thickness. Each tower leg was anchored to bedrock with 2 rock anchors as shown in Figure 3. The rock anchors consisted of a 25 mm diameter smooth mild steel bar with a wedge at the bottom and grouted into rock.

4.0 PREPARATIONS FOR TOWER TESTS

4.1 Test Site Layout and Equipment

Preparations for performing the tower tests involved among other things planning and preparing the site layout. Figure 4 shows the site layout for the tests on Towers 66 and 67 and the test site layout for Tower 65 is shown in Figure 5.

A 40-ft site trailer was used as an office, a conference and a lunch room for the staff. The electric power for this trailer was obtained from a portable generator. A 20 ft instrumentation trailer (Figure 6) housed all the data acquisition systems and other related equipment. Uninterruptible power was provided to the instrument trailer from the nearby distribution line.

An 80-ton capacity hydraulic crane, equipped with double buckets, Figure 7, was used to handle the test equipment, erect the reaction X17S structure, and lift men to both towers. A 50 ft or a 75 ft bucket truck was also used to strain gauge tower members when the hydraulic crane was unavailable.

A bulldozer (Figure 8) with a winch was used to apply the along-the-line loads. A radial boom derrick (RBD) was used to supply pressure to hydraulic jacks lifting the dead weights on the test tower and to lift the hydraulic cylinder which was used to apply the along-the-line loads to the test tower. A backhoe was used to lift the hydraulic cylinder at Tower 67 because of the swamp conditions.

4.2 Rigging of Test Tower

The preparation of each test tower required about 7 working days which does not include the time for the fabrication of special connectors and acquiring all the rigging and instrumentation. To secure the tower from toppling over should a leg fail, four rock anchors, with guy wires, Figure 9, were installed.

The hydraulic cylinders, used to apply the vertical loads on the towers, were installed on each tower prior to the tests. Special connectors were designed to fasten the load cells to the tower at the insulator attachment points. Details on typical attachments are shown in Figures 10-12. These connectors were designed for applying simultaneously the vertical, along-the-line and transverse loads as well as to attach a displacement target. The skywire connection consisted of two chain slings, one on either side, bolted to the skywire plate. The end of each sling was shackled to a yoke plate beneath the skywire connection, Figure 11. Before mounting the load cells, their calibrations were checked by suspending known weights from a crane. The initial calibrations for the load cells were performed in the Mechanical Research Department laboratory prior to the tower tests. The load cells with the computer were calibrated as a system in a 120 kip capacity universal testing machine whose calibration is traceable to NRC in Ottawa. The load cells, housed inside a special safety frame, were bolted to the special connectors or shackled to the yoke plate at the skywire location. A plastic

shroud was used to protect each load cell from snow or rain. Safety slings were used to secure the load cells to the main tower structure. Optical survey targets were fastened to the tower structure at nine locations.

4.3 Rigging of Reaction Tower

An 80 ft base section of a X17S, single pole, steel tower was used for applying the transverse loads to the test towers. A steel base frame, Figure 13, was fabricated for anchoring the reaction tower to the special concrete footings. The transverse loads were transferred from the reaction tower to the test towers by means of wire ropes which were attached to the reaction tower by way of a custom built frame (Figure 14). The transverse loads were generated by using four 10-ft stroke hydraulic cylinders (Figure 15) mounted at the base of the reaction tower. The custom frame was designed such that the position of the transverse loads could be raised or lowered according to the ground elevations of the reaction tower. The erected tower is shown in Figure 14 with the two safety guys. One of the guys was strain gauged to measure the tension.

The reaction tower was secured with four main guys and two safety guys. The tension of the four 45° main guys and two 180° safety guys was specified to be 5,000 lb and 2,000 lb respectively.

5.0 ARRANGEMENTS FOR APPLYING LOADS ON TOWERS

5.1 Vertical Loads

The vertical loads on the towers were applied by hydraulic cylinders lifting or uplifting against steel weights. Figure 16 details the typical vertical load hardware used in testing towers 66 and 67. The maximum vertical loads for the three conductors and skywire locations for towers 66 and 67 were 4400 lbs and 4800 lbs respectively. A 400 lb weight was placed on top of the stack shown in Figure 16 for the skywire location. Figures 17 & 18 show some details of vertical load rigging. Four 3-ft stroke, double acting, hydraulic cylinders were suspended - one from each conductor and one from the skywire connection. For all the tests the hydraulic cylinders were fully extended and each was connected to a stack of steel weights with slings and shackles. The weights were equal to the required loads for each test.

The hydraulic cylinders were powered by oil pressure supplied from a central hydraulic station (Figure 19) which received the oil supply from a RBD. The hydraulic station was located to one side and well behind the test tower.

5.2 Along-the-Line Loads

The along-the-line loads were applied by means of a bulldozer or a hydraulic cylinder attached to a bulldozer. Figure 20 shows the arrangement of the along-the-line pull rigging. The rigging was designed to apply a 15,000 lb horizontal pull with 3.5 safety factor. Figure 21 shows the equipment used

for applying the along-the-line load. The bulldozer was stationed at a maximum practical distance away from the test tower. A survey crew staked out the exact location for along-the-line pull at each tower site. This ensured that the along-the-line load was applied parallel to the tower line.

After the vertical loads were applied by lifting the dead weights by hydraulic cylinders, the along-the-line loads were applied slowly by inching the bulldozer forward and away from the tower. This initial loading was accomplished by gripping the pulling cable with a cable grip attached to the bulldozer winch line. Once the pulling cable was clear of the ground, a 10 ft stroke, hydraulic cylinder (suspended from a RBD and attached to the bulldozer draw bar) was attached to the end of the pulling cable. After the transfer was made, all subsequent loading was carried out by the hydraulic cylinder powered by a gasoline driven hydraulic pump stationed well away from the line of pull.

5.3 Transverse Loads

The transverse loads were applied by four 10-ft stroke hydraulic cylinders attached to the same base structure as the reaction tower. All four cylinders were controlled by a valving station and a separate hydraulic pump located beside the instrument trailer. Figure 22 illustrates the transverse load rigging and Figure 23 shows the test and reaction towers set for applying transverse loads. The rigging was designed such that a 6000 lb load could be applied on each of the three conductor attachment points together with a 4500 lb load on the skywire attachment point.

6.0 TEST PROCEDURES

The test procedure for performing all the tests was to take zero readings on all instruments and then load the test tower incrementally until either the maximum loads agreed upon with Transmission Line Design were reached or any tower failure occurred. After reaching each load increment, all loads, strains, and footing and tower displacements were recorded. Continuous recordings of several important measurements were also done during the tests. Care was taken to prevent towers 66 and 67 from failing before the transverse load was applied. The proposed test order for tower 65 was Tests A, D1, D3 and D2 to destruction. Test B was not scheduled to be performed on tower 65. When the maximum desired load or failure was attained for each separate test, the load was released gradually.

6.1 Test A: Heavy Ice Condition

For Test A each tower was subjected only to vertical loading. The load steps and the applied loads on each conductor and the skywire are summarized in Table I. Initially, the rate of loading on each tower was approximately 600 lb/minute for steps A-1 to A-3, after which the rate decreased to about 400 lb/minute for load steps A-4 and beyond. The following maximum loads (Table I), were applied on each tower.

Tower No.	Load Step	Load on Skywire	Load on Each Conductor (lbs)	Total Load (lbs)
66	A-6	3840	3520	14,400
67	A-4	2880	2640	10,800
67	A-8	4800	4400	18,000
65	A-12	6720	6160	25,200

6.2 Test D1: Broken Skywire Condition

After readjusting for the proper vertical weights the zero readings were recorded and the pulling line with a load cell and an angle indicator was attached to the skywire location. For tower 65 the pulling line was attached to a steel plate bolted at the junction of all the tower angles, 6" below the skywire connection. The bulldozer at the other end of the pulling line was slowly moved along until a load of 500 lb was reached. After taking a set of readings, all the vertical weights were lifted to a height of approximately 16 inches above ground and another set of readings was taken. The 2000 lb along-the-line load was accomplished by moving the bulldozer forward. Subsequent loadings were achieved by using the hydraulic cylinder attached to the bulldozer. The rate of loading for all the along-the-line loads was approximately 200 lb/minute. The following maximum along-the-line loads (Table II) were applied to each tower.

Tower No.	Load Step	Maximum Along-the-Line Load (lb)*
66	D1-4	3400
67	D1-4	3400
65	D1-11	to 7600

*not adjusted for the pulling line angle

6.3 Test D2: Broken Outside Conductor Condition

The zero readings were taken after the pulling line was reattached to the outside conductor and the bulldozer was repositioned to be directly opposite the outside conductor. Another set of readings was taken after all the vertical weights were lifted off the ground. The bulldozer was then slowly moved in the same manner as in the previous tests until reaching a load of 1875 lb. After installing the 10 ft stroke hydraulic cylinder all subsequent loading was carried out hydraulically. The same rate of loading was used as in Test D1. The table below summarizes the maximum along-the-line loads, (Table III), that were applied for each tower.

Tower No.	Load Step	Maximum Along-the-Line Load (lb)*
66	D2-5	3560
67	D2-10	4500

*not adjusted for the pulling line angle

6.4 Test D3: Broken Centre Conductor Condition

After connecting the pulling line to the centre conductor and realigning the bulldozer, the zero readings were taken. Once the vertical weights were off the ground another set of readings was taken. For tower 66 one more set of readings was taken after a 500 lb along-the-line load was reached. When a 2000 lb along-the-line load was reached for both towers 66 and 67, another set of readings was taken and the remainder of the loading was performed hydraulically until the maximum along-the-line loads given below (Table IV) were attained.

Tower No.	Load Step	Maximum Along-the-Line Load (lb)*
66	D3-3	5630
67	D3-10	9000

*not adjusted for the pulling line angle

6.5 Test B: High Wind and Ice Load (Wind-on-Ice Load) Condition

Test B was started once all four slings were pretensioned to approximately 150 lb to take up most of the slack between the test and reaction towers. For tower 66, the skywire pulling cable was attached directly to the skywire angle projection, while for tower 67 the same pulling cable was attached at the junction of all the tower angles, 6 inches below the skywire connection. After the vertical weights were lifted off the ground another set of readings was taken. All subsequent loadings were then carried out by applying the transverse loads to the tower by the 10 ft stroke hydraulic cylinders located near the base of the reaction tower. The tower was loaded at a rate of 500 lb/minute up to Test Step B-4, after which the rate of loading was decreased by about 50 percent. Each tower was tested to destruction.

7.0 MODES OF TOWER FAILURE

The different modes under which the three towers failed will be illustrated.

7.1 Towers 66 and 67

As indicated earlier the loading type and sequence on towers 66 and 67 were similar except for some minor variations. Both the towers failed under the wind-on-ice load combination at about the predicted load level. The first local failure observed in each tower was the buckling of a horizontal member as shown in Figure 24. Almost immediately following the local failure the structure started to collapse as shown in Figure 25.

7.2 Tower 65

As noted earlier in the report, tower 65 was scheduled to be subjected to loadings only due to broken skywire and conductor. However, the tower failed locally during the broken skywire loading (Figure 26) and hence no further testing was carried out on the tower.

8.0 DATA ANALYSIS

The data gathered during the tests on towers 65,66 and 67 have been analysed in detail in Part 3 of this report.

TABLE I
LOAD STEPS FOR TEST A: HEAVY ICE CONDITION

LOAD STEPS	VERTICAL LOADS (LB) AT			
	SKYWIRE	CONDUCTORS		
	PT 2*	PT 3*	PT 4*	PT 5*
A-1	1200	1100	1100	1100
A-2	1800	1650	1650	1650
A-3+	2400	2200	2200	2200
A-4	2880	2640	2640	2640
A-5	3360	3080	3080	3080
A-6	3840	3520	3520	3520
A-7	4320	3960	3960	3960
A-8	4800	4400	4400	4400
A-9	5280	4840	4840	4840
A-10	5760	5280	5280	5280
A-11	6240	5720	5720	5720
A-12	6720	6160	6160	6160

* see Figure 1 for location
\+ corresponds to Load I in Figure 1

TABLE II
LOAD STEPS FOR TEST D1: BROKEN SKYWIRE CONDITION

LOAD STEPS	LOADS (LB) AT				
	SKYWIRE		CONDUCTORS		
	VERTICAL LOAD PT 2*	ALONG-THE LOAD PT 2*	VERTICAL LOADS		
			PT 3*	PT 4*	PT 5*
D1-1	2400	500	2200	2200	2200
D1-2	2400	2000	2200	2200	2200
D1-3	2400	3000	2200	2200	2200
D1-4	2400	3400	2200	2200	2200
D1-5	2400	3600	2200	2200	2200
D1-6+	2400	4000	2200	2200	2200
D1-7	2400	4800	2200	2200	2200
D1-8	2400	5600	2200	2200	2200
D1-9	2400	6400	2200	2200	2200
D1-10	2400	7200	2200	2200	2200
D1-11	2400	7600	2200	2200	2200

* see Figure 1 for location
\+ corresponds to Load IIIc, in Figure 1

TABLE III
LOAD STEPS FOR TEST D2: BROKEN OUTSIDE CONDUCTOR CONDITION

LOAD STEPS	LOADS (LB) AT				
	SKYWIRE VERTICAL LOAD	CONDUCTORS			
		VERTICAL LOADS			ALONG-THE-LINE LOAD
	PT 2*	PT 3*	PT 4*	PT 5*	PT 5*
D2-1	2400	2200	2200	2200	500
D2-2	2400	2200	2200	2200	1875
D2-3	2400	2200	2200	2200	2800
D2-4	2400	2200	2200	2200	3190
D2-5	2400	2200	2200	2200	3560
D2-6+	2400	2200	2200	2200	3750
D2-7	2400	2200	2200	2200	3940
D2-8	2400	2200	2200	2200	4130
D2-9	2400	2200	2200	2200	4310
D2-10	2400	2200	2200	2200	4500

* See Figure 1
+ Corresponds to load IIIb, in Figure 1

TABLE IV
LOAD STEPS FOR TEST D3: BROKEN CENTRE CONDUCTOR CONDITION

LOAD STEPS	LOADS (LB) AT				
	SKYWIRE	CONDUCTORS			
	VERTICAL LOAD PT 2*	VERTICAL LOAD PT 3*	VERTICAL LOAD PT 4*	ALONG-THE-LINE LOAD PT 4*	VERTICAL LOAD PT 5*
D3-1	2400	2200	2200	2000	2200
D3-2	2400	2200	2200	3750	2200
D3-3	2400	2200	2200	5630	2200
D3-4	2400	2200	2200	6380	2200
D3-5	2400	2200	2200	6750	2200
D3-6+	2400	2200	2200	7500	2200
D3-7	2400	2200	2200	7880	2200
D3-8	2400	2200	2200	8250	2200
D3-9	2400	2200	2200	8630	2200
D3-10	2400	2200	2200	9000	2200

* See Figure 1
+ Corresponds to load IIIa, in Figure 1

TABLE V

LOAD STEPS FOR TEST B: HIGH WIND & ICE LOAD (WIND-ON-ICE LOAD) CONDITION

LOAD STEPS	VERTICAL LOADS (LB) AT				
	SKYWIRE	CONDUCTORS			
	PT 2*	PT 3*	PT 4*	PT 5*	
B-1	0	0	0	0	
B-2	2460	2200	2200	2200	Remained suspended during rest of test
	TRANSVERSE LOADS (LB) AT				
	SKYWIRE	CONDUCTORS			
	PT 2*	PT 3*	PT 4*	PT 5*	
B-3	750	1000	1000	1000	
B-4	1130	1500	1500	1500	
B-5	1280	1700	1700	1700	
B-6	1430	1900	1900	1900	
B-7+	1500	2000	2000	2000	
B-8	1650	2200	2200	2200	
B-9	1800	2400	2400	2400	
B-10	1950	2600	2600	2600	
B-11	2030	2700	2700	2700	
B-12	2100	2800	2800	2800	
B-13	2250	3000	3000	3000	
B-14	2400	3200	3200	3200	

* see Figure 1 for location

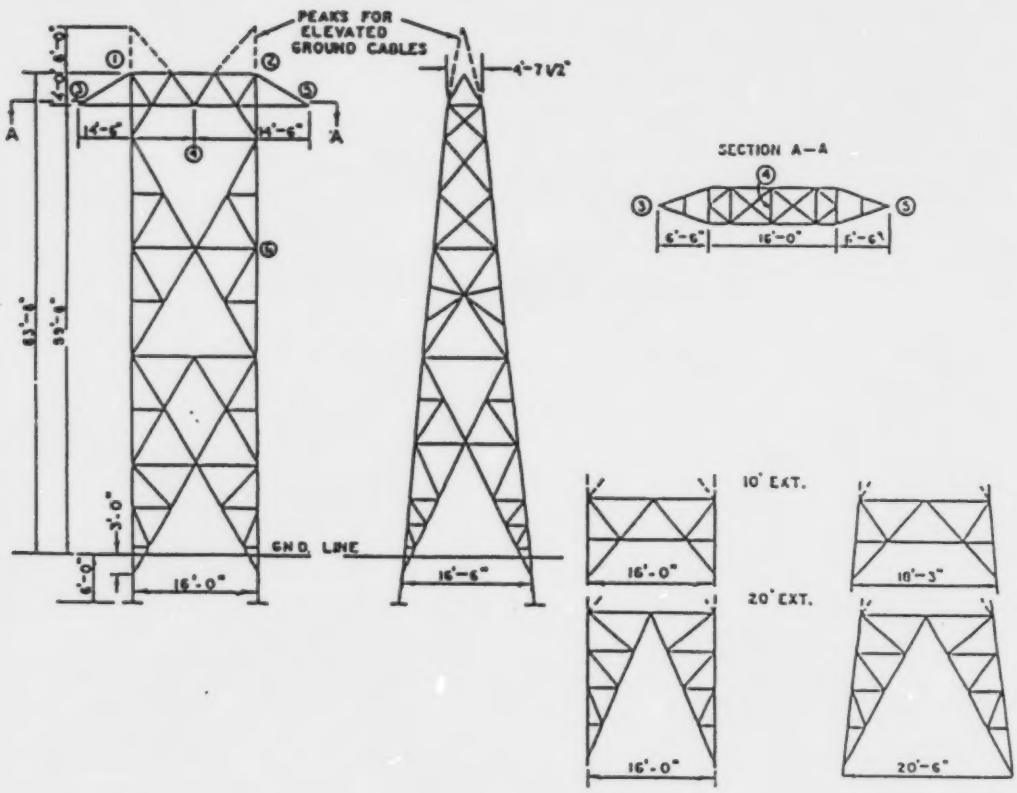
\+ corresponds to Load II, in Figure 1

TABLE VI
TIME SCHEDULE FOR TOWER TESTING

DATE	TOWER 66	TOWER 67	TOWER 65
FEB. 29 M	Travel, Off-Loaded Equipment		
MAR. 1 M	Strain Gauging, Pole Erection		
MAR. 2 W	Strain Gauging, Power Supply		
MAR. 3 Th	Strain Gauging, Completed Set-up Weather Station Set-up		
MAR. 4 F	Rigging, Weather st., Travel		
MAR. 7 M	Travel, Strain Gauging, Rigging Computer Set-up, Calibration		
MAR. 8 Tu	Rigging, Instrumentation	Strain Gauging	
MAR. 9 W	Rigging & Instrumentation Excavating Footings	Strain Gauging, Excavating Footings	
MAR. 10 Th	Test A	Strain Gauging	
MAR. 11 F	Test D1, Travel	Strain Gauging, Travel	
MAR. 14 M	Travel, Rigging		
MAR. 15 Tu	Test D2 and D3		
MAR. 16 W	Rigging for Test B		
MAR. 17 Th	Test B, Dismantling		
MAR. 18 F	Dismantling, Travel		
MAR. 21 M	Travel, Dismantle		
MAR. 22 Tu	Move Trailer & Pole	Set-up Trailer	
MAR. 23 W		Power Supply	
MAR. 24 Th		Erect Pole	
MAR. 25 F		Rigging, Travel	

TABLE VI (CONTINUED)

DATE	TOWER 66	TOWER 67	TOWER 65
MAR. 28 M		Travel, Rigging	
MAR. 29 Tu		Rigging	
MAR. 30 W		Instr. & Calibration	
MAR. 31 Th		Instr., Travel	
APR. 1 F		Good Friday	
APR. 4 M		Easter Monday	
APR. 5 Tu		Travel, Calibration	Strain Gauge
APR. 6 W		Test A and Test D1	Strain Gauge
APR. 7 Th		Test D2 and Test D3	Strain Gauge
APR. 8 F		Travel	
APR. 11 M		Travel, Rigging	
APR. 12 Tu		Redo Test A, Rigging	
APR. 13 W		Test B	
APR. 14 Th		Dismantle	
APR. 15 F		Travel	
APR. 18 M		Travel, Dismantle	
APR. 19 Tu		Move Trailer	Set-up Trailer
APR. 20 W		Ship Pole	Rigging
APR. 21 Th			Rigging, Instr.
APR. 22 F			Calibration, Travel
APR. 25 M			Travel, Test A
APR. 26 Tu			Test D1, Dismantle
APR. 27 W			Dismantle, Travel



LOADS:

I VERTICALLY DOWNWARD

1200 lbs. at one point 1 or 2 and 2200 lbs. at points 3,4, and 5 and 1200 lbs. at point 6

II HORIZONTALLY, NORMAL TO DIRECTION OF LINE

1500 lbs. at one point 1 or 2 and 2000 lbs. at points 3,4, and 5 and 1000 lbs. at one point 6

III HORIZONTALLY, PARALLEL TO DIRECTION OF LINE

a) 7500 lbs. at point 4 or b) 3750 at points 3 or 5, or c) 4000 lbs. at one point 1 or 2

IV WEIGHT OF STRUCTURE

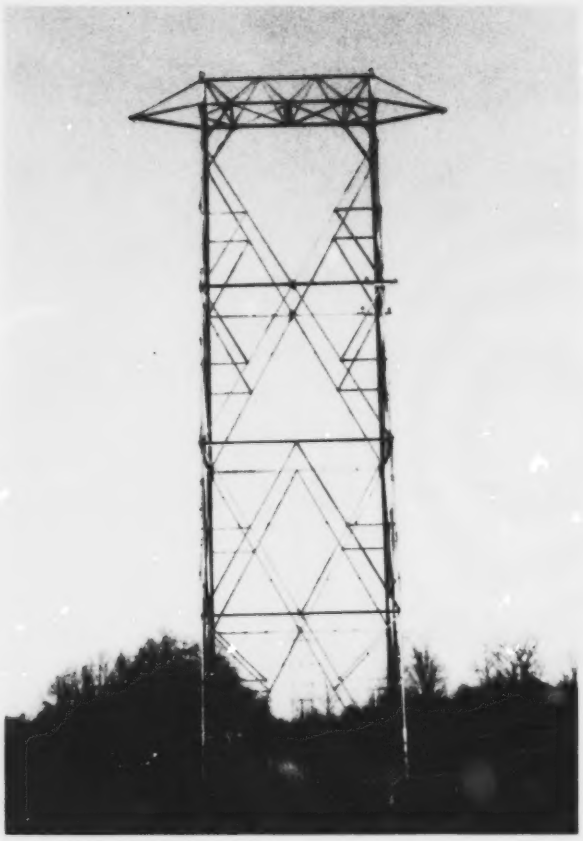
LOAD COMBINATIONS: (A) I,II AND IV
OR (B) I,III AND IV
OR (C) TWICE I ALONE

DATA:

Conductor Size : 477,000 cm ACSR
Conductor Max. Tension : 7500 lbs.
Ground Cable Size : 3/16 in. steel
Ground Cable Max. Tension : 4,000 lbs.
Normal Span : 1000 ft.
Max. Deflection Angle with Normal Span : 3
Max. Tangent Span : 1380 ft.
Weight of Tower : 3955 lbs
Weight of Footing : 516 lbs
Equivalent Delta Spacing : 18.27 ft

FIGURE 1

DETAILS ON 115 kV SINGLE CIRCUIT KINGSTON TYPE SUSPENSION TOWER

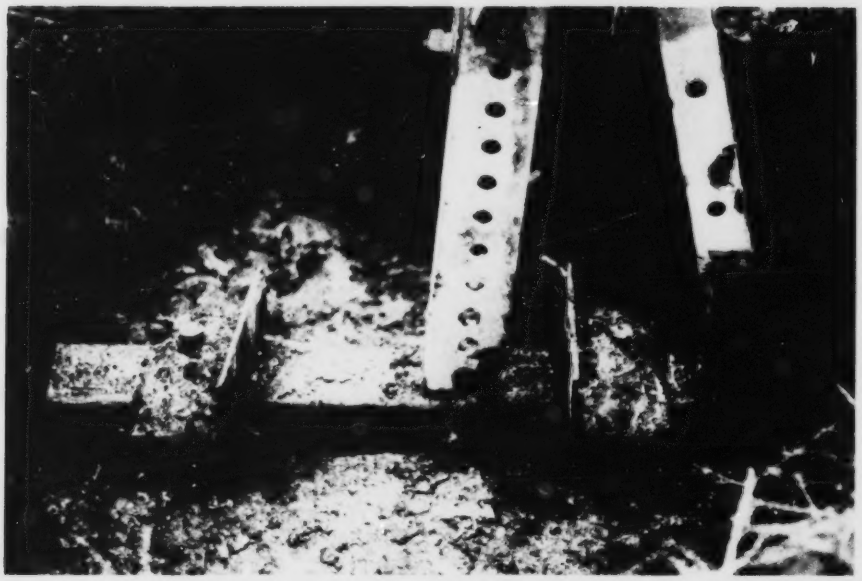


ALONG-THE-LINE VIEW

AN ANGLE VIEW

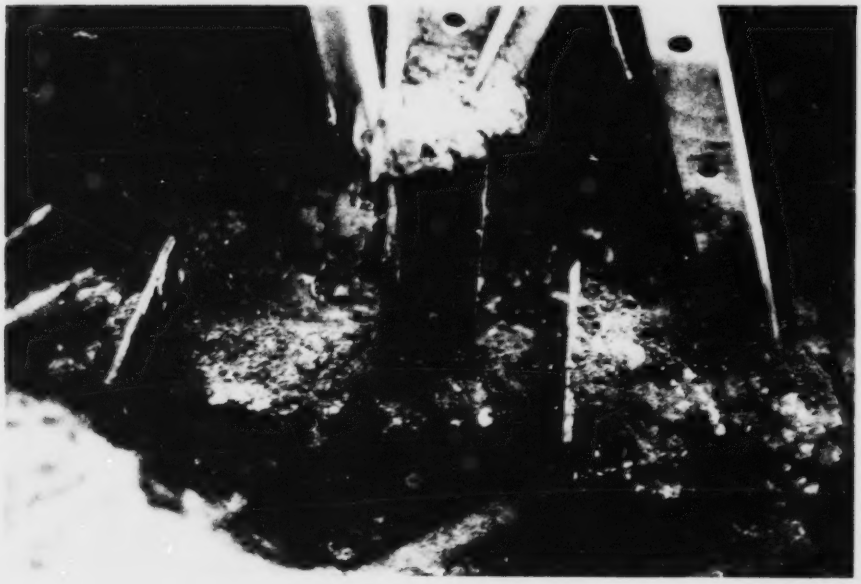
FIGURE 2
DIFFERENT VIEWS OF A TYPICAL KINGSTON TYPE SUSPENSION TOWER (TOWER #66)

89-79
176270-K3-RD



TOWER # 66

SURFICIAL RUST ON CROSS-MEMBER NOT SEEN ON MAIN TOWER LEG ABOVE GROUND SURFACE



TOWER # 67

ROCK ANCHOR FOUNDATIONS EXCAVATED WITH 1 TO 2 ft OVERBURDEN

FIGURE 3

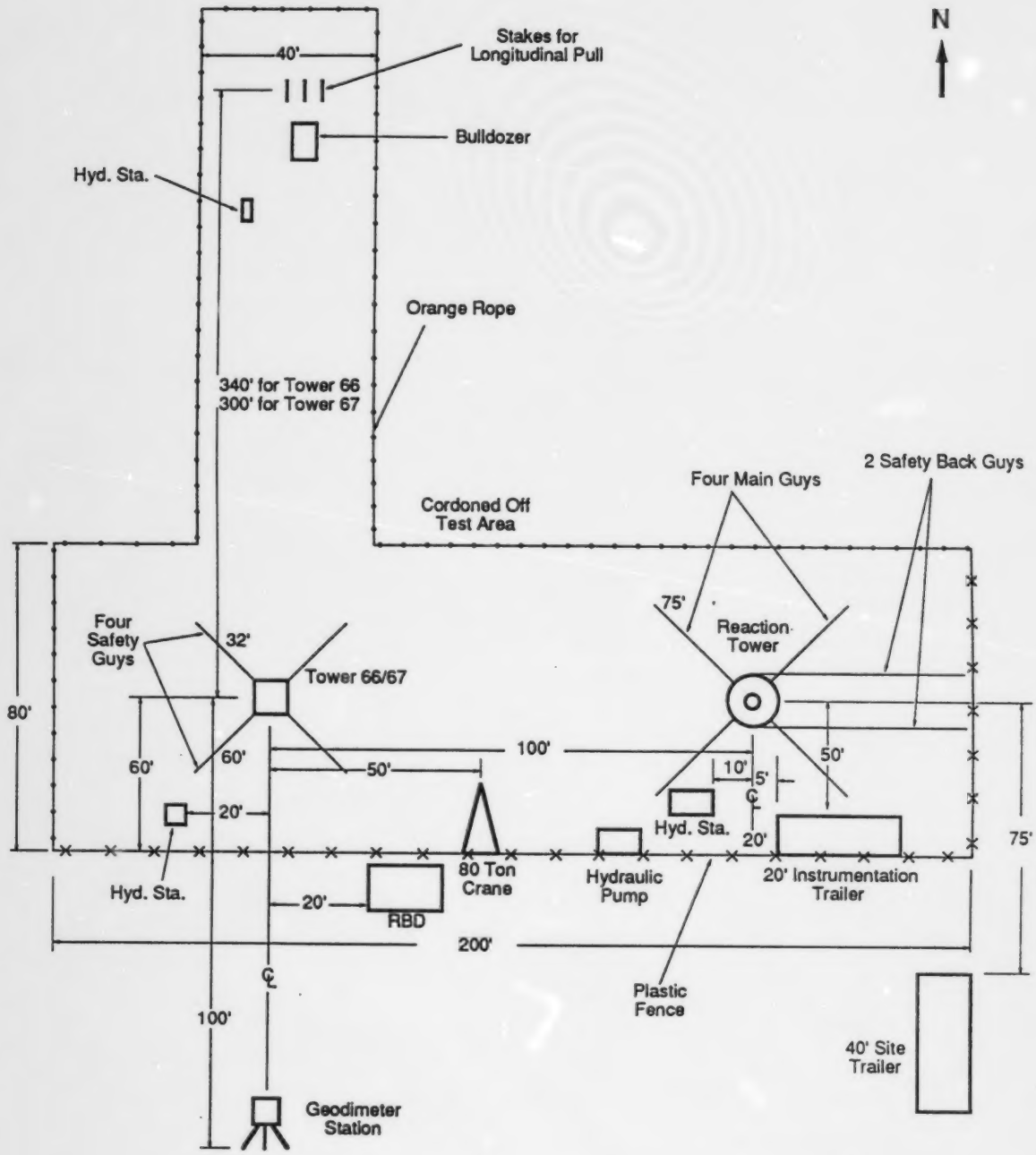


FIGURE 4

SITE LAYOUT FOR TOWERS 66 AND 67

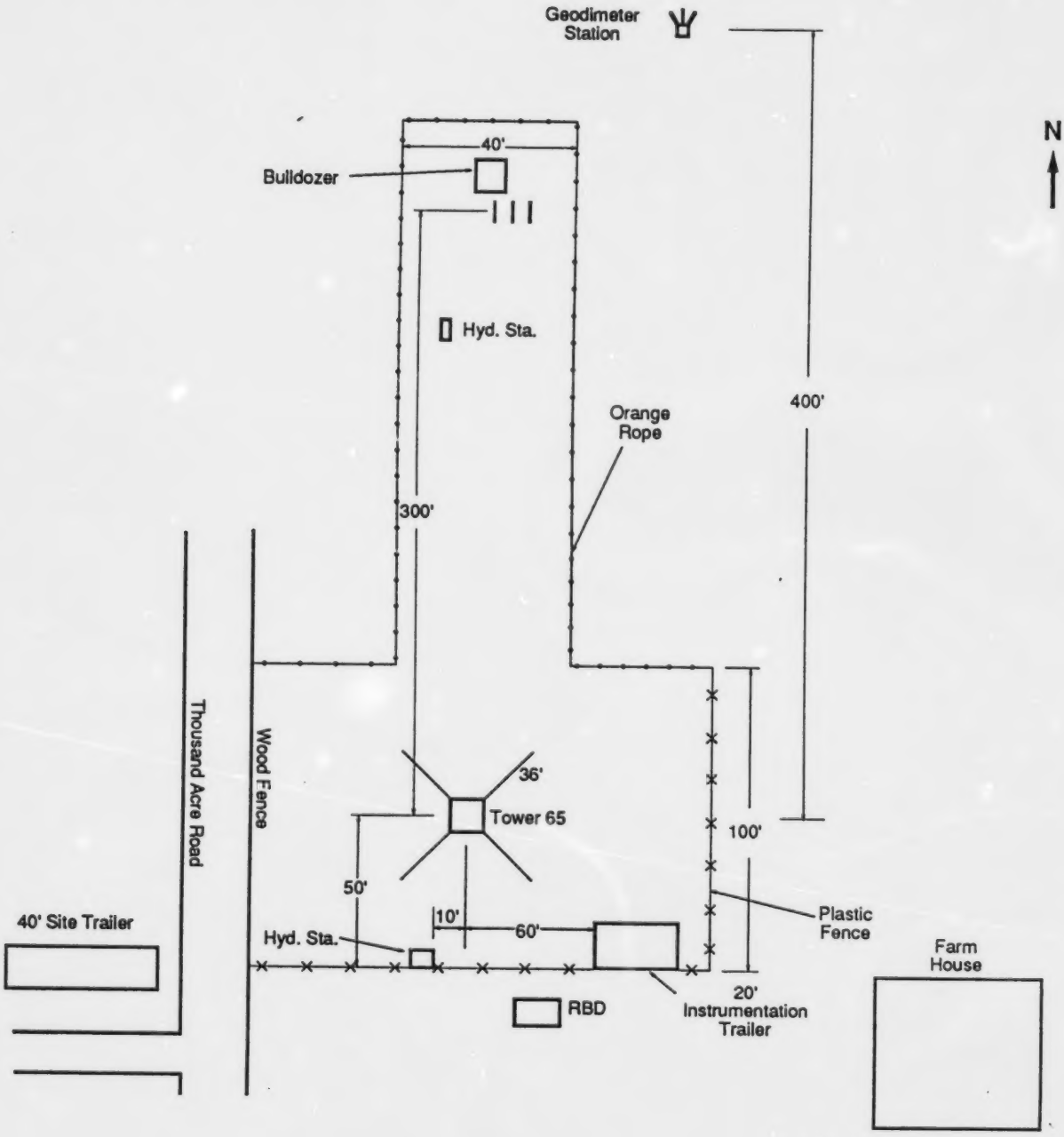


FIGURE 5

SITE LAYOUT FOR TOWER 65

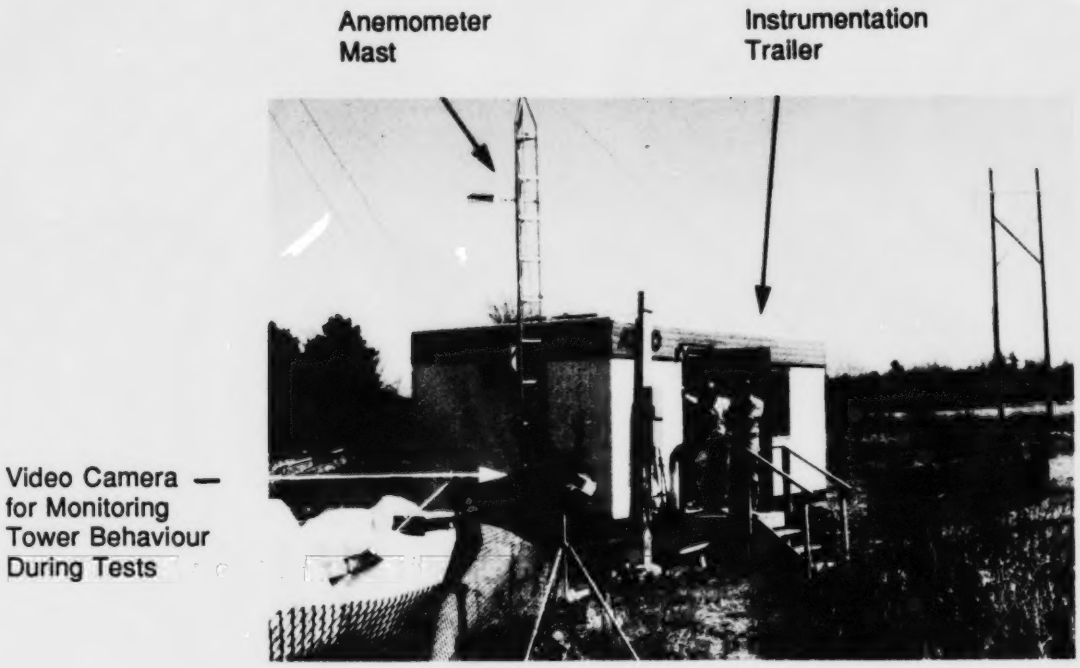


FIGURE 6

INSTRUMENTATION TRAILER

FIGURE 7

80-TON CRANE WITH BUCKETS

89-79
178276-K3-RD

FIGURE 8

ALONG-THE-LINE LOADS, TEST D3, BEING APPLIED TO TOWER 66 BY A HYDRAULIC CYLINDER ATTACHED TO THE BULLDOZER

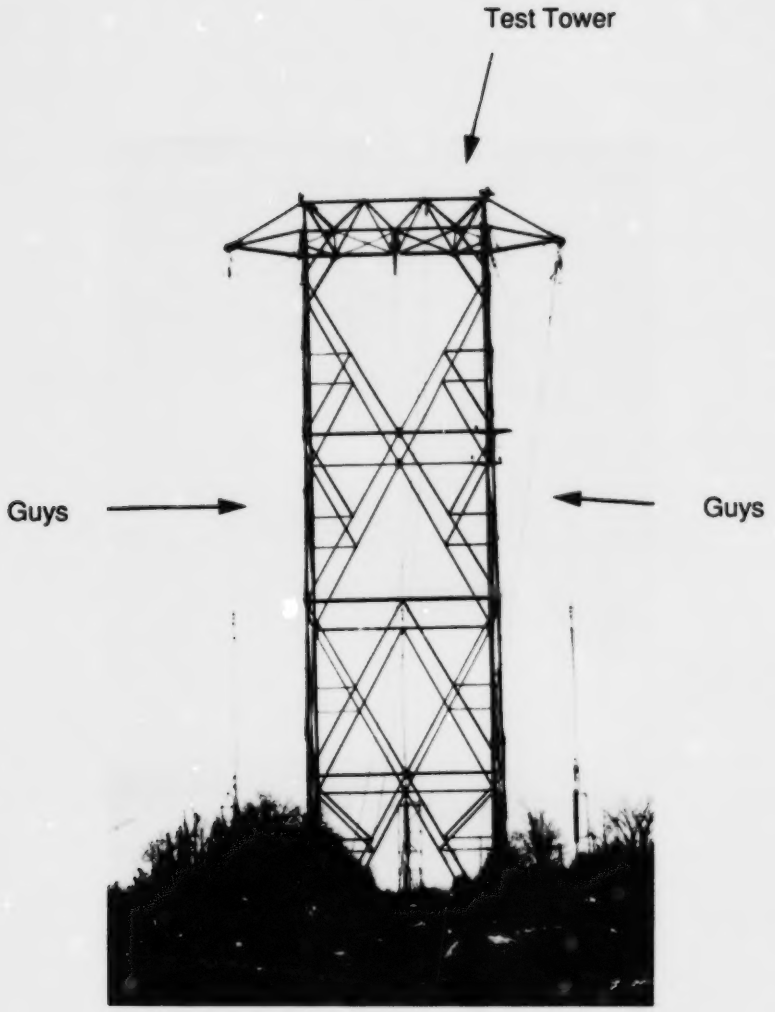


FIGURE 9

FOUR GUY WIRES SECURING TEST TOWER

89-79
178278-K3-RD

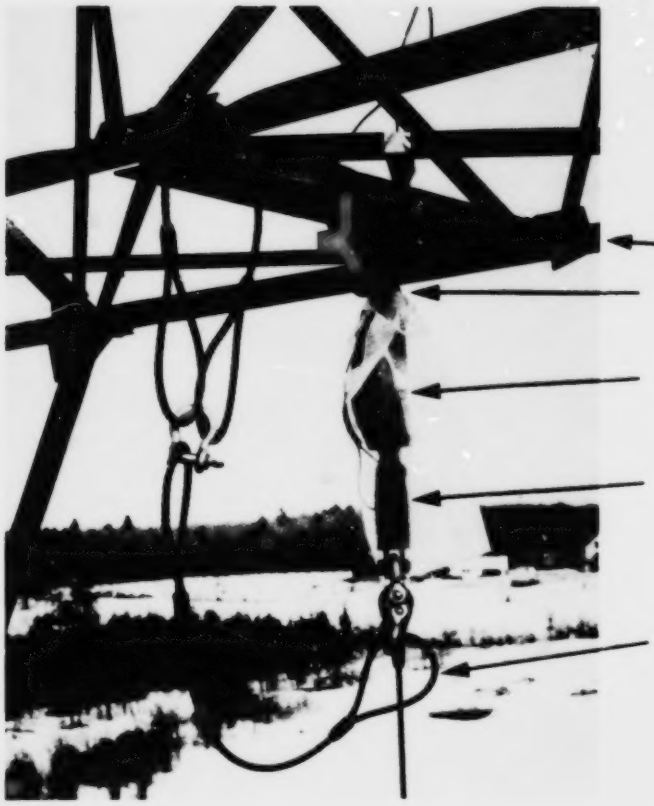


FIGURE 10

CENTRE CONDUCTOR RIGGING, POINT 3

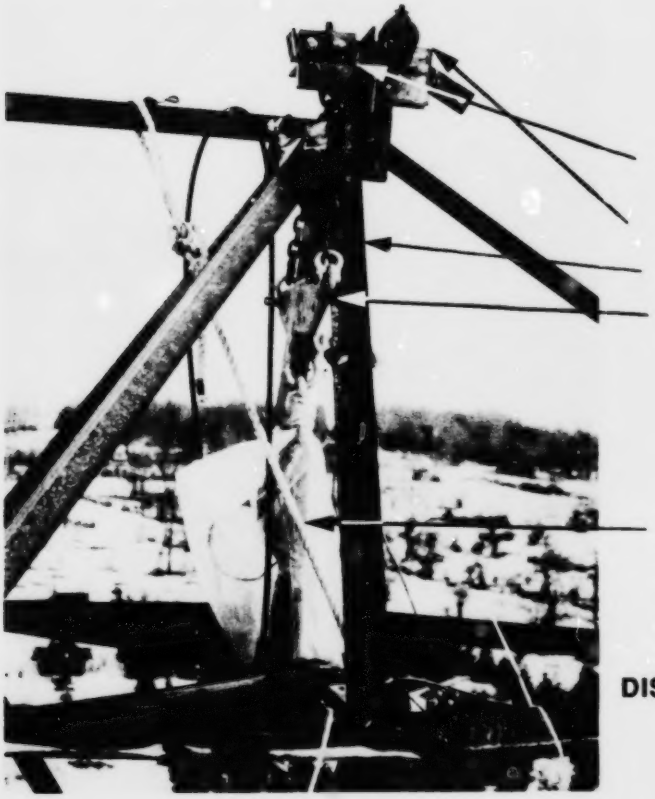


FIGURE 11

SKYWIRE RIGGING AND DISPLACEMENT INSTRUMENTATION FOR TOWER 66, POINT 2

178280-K3-RD

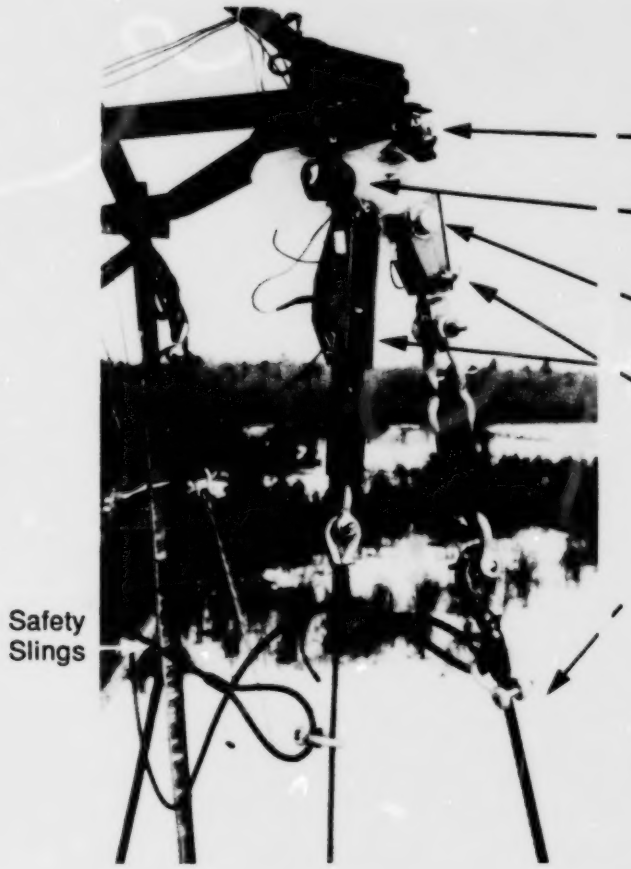


FIGURE 12

CLOSE-UP OF EAST CONDUCTOR ARM, POINT 5 RIGGING AND INSTRUMENTATION

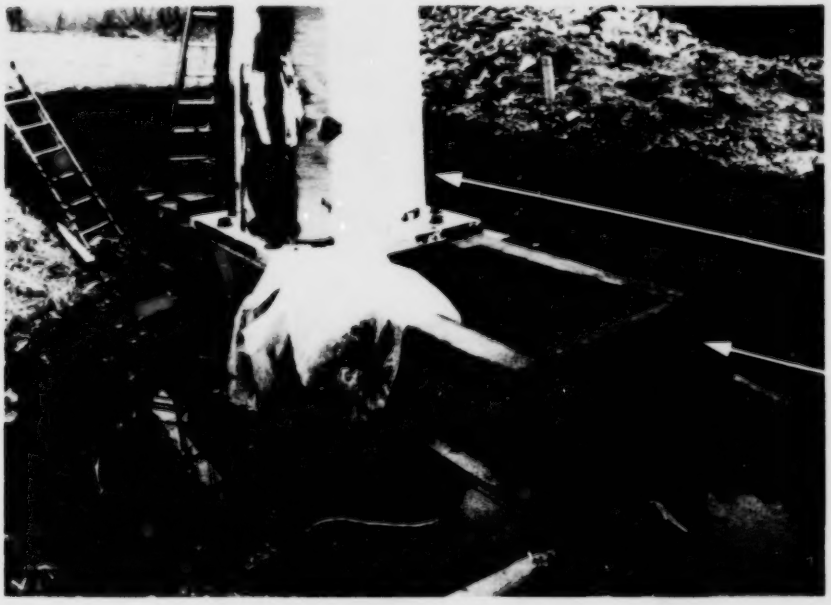


FIGURE 13

REACTION TOWER FOOTINGS AND STEEL BASE FRAME

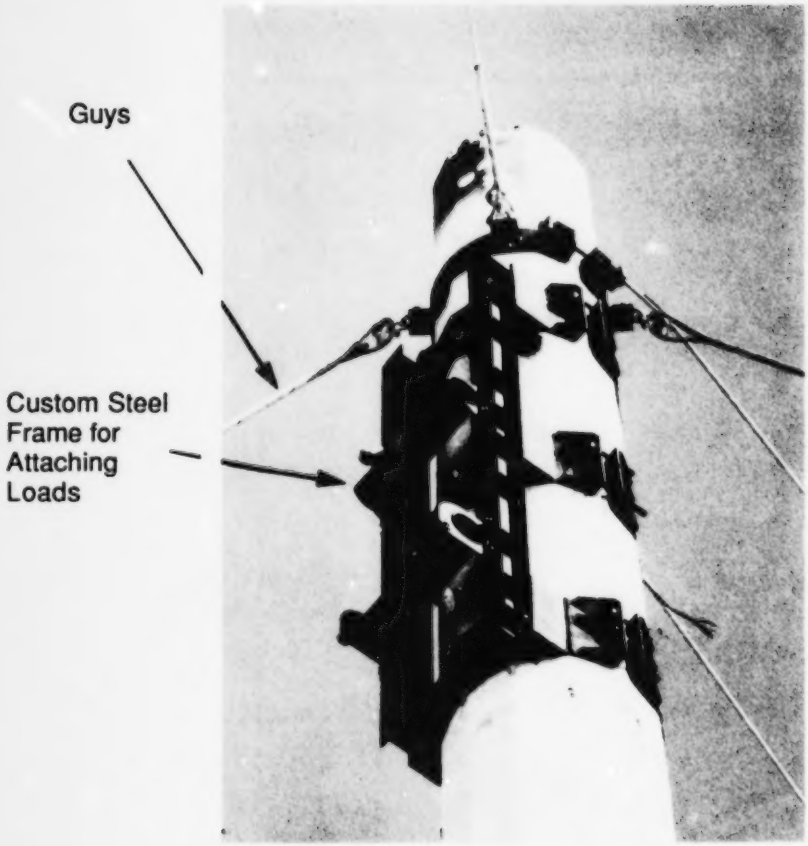


FIGURE 14

CUSTOM FRAME MOUNTED NEAR TOP OF THE REACTION TOWER

FIGURE 15

10' STROKE HYDRAULIC CYLINDERS AT BASE OF REACTION TOWER FOR APPLYING THE TRANSVERSE LOADS

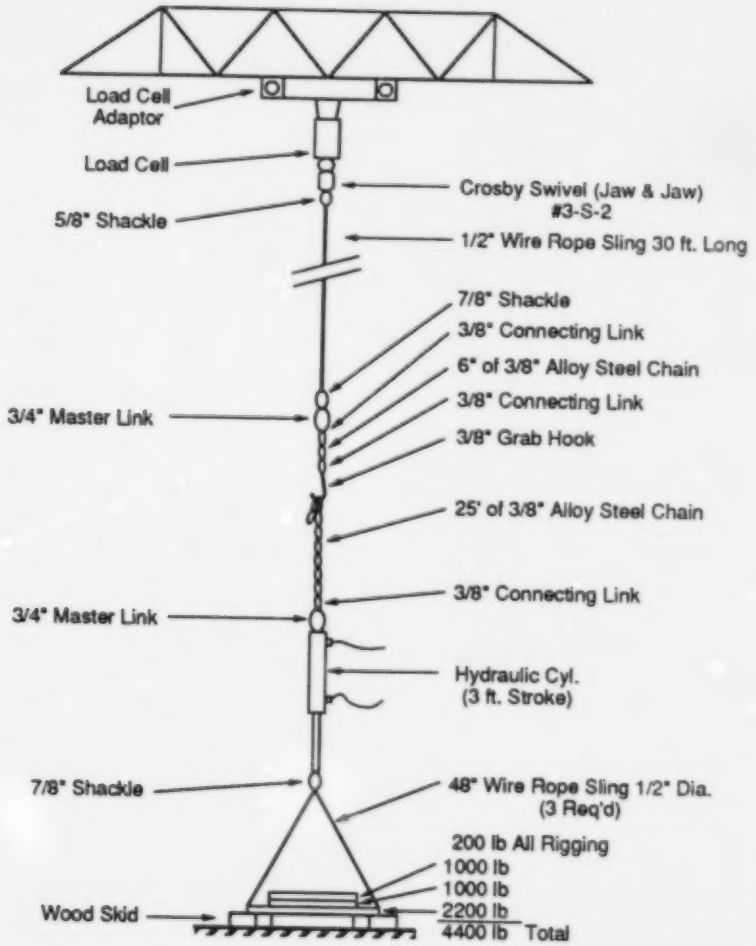


FIGURE 16

SCHEMATIC OF VERTICAL LOAD RIGGING

FIGURE 17

HYDRAULIC CYLINDERS WITH STEEL WEIGHTS, TEST ARRANGEMENT FOR TEST A: HEAVY ICE FOR TOWERS 66 AND 67

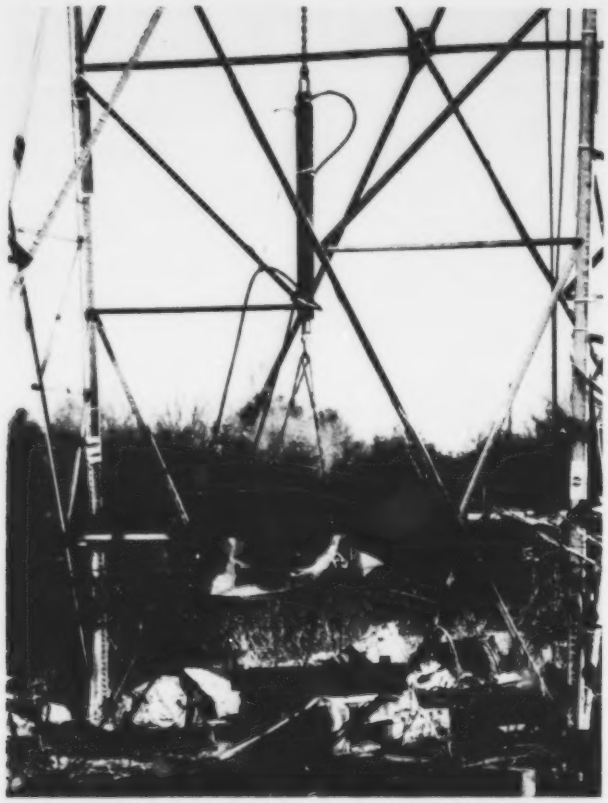


FIGURE 18

CLOSE-UP OF 3' STROKE HYDRAULIC CYLINDER, AIRBORN STEEL WEIGHT ON CENTRE CONDUCTOR, IN TESTS D1, D2, D3 AND B

FIGURE 19

HYDRAULIC STATION FOR APPLYING THE VERTICAL LOADS

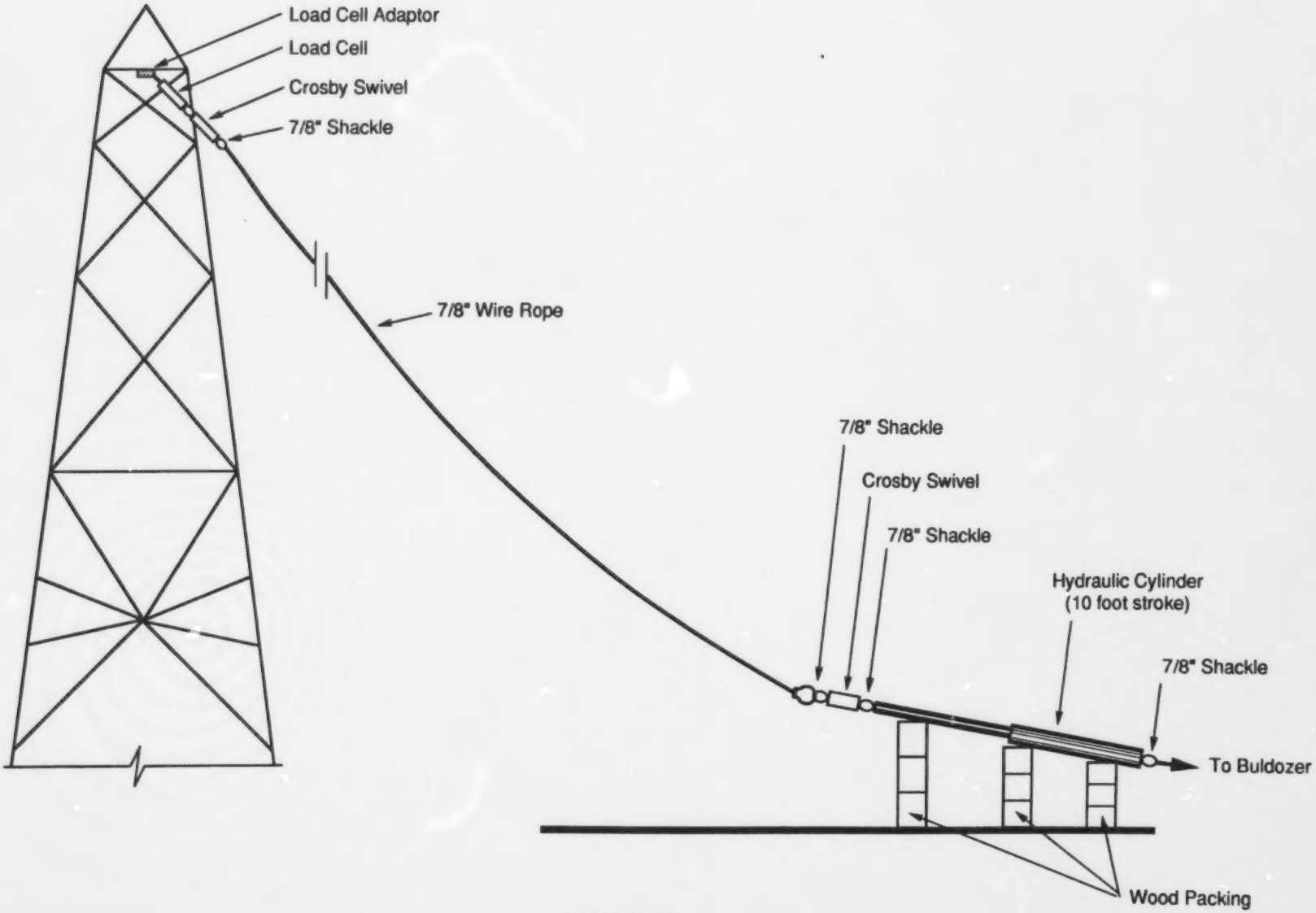


FIGURE 20

ARRANGEMENT FOR LONGITUDINAL PULL RIGGING

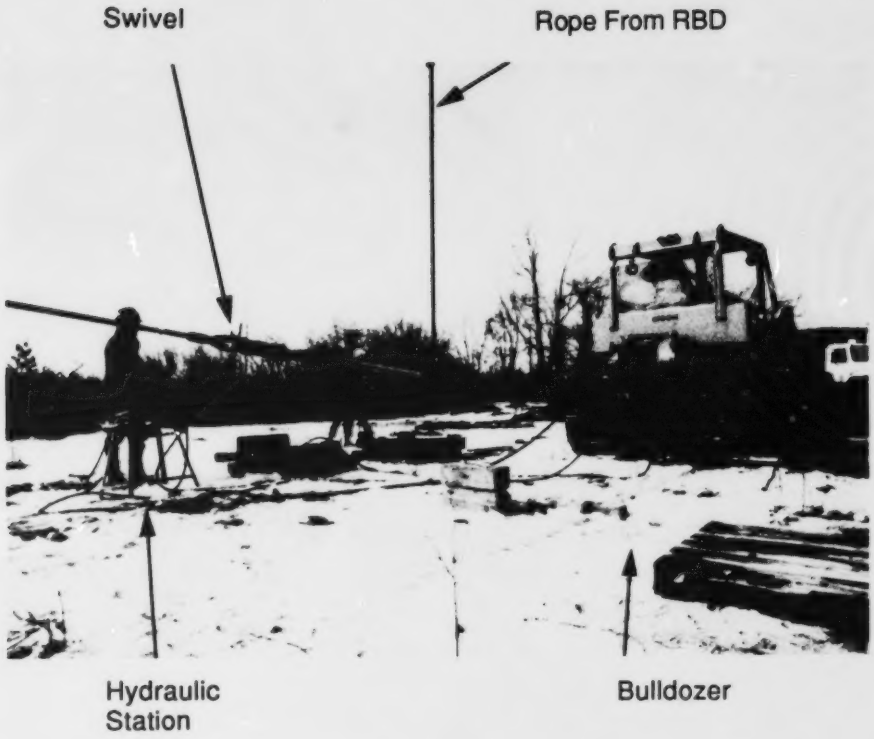


FIGURE 21

APPLYING LONGITUDINAL LOADS BY HYDRAULIC CYLINDER ATTACHED TO A BULLDOZER

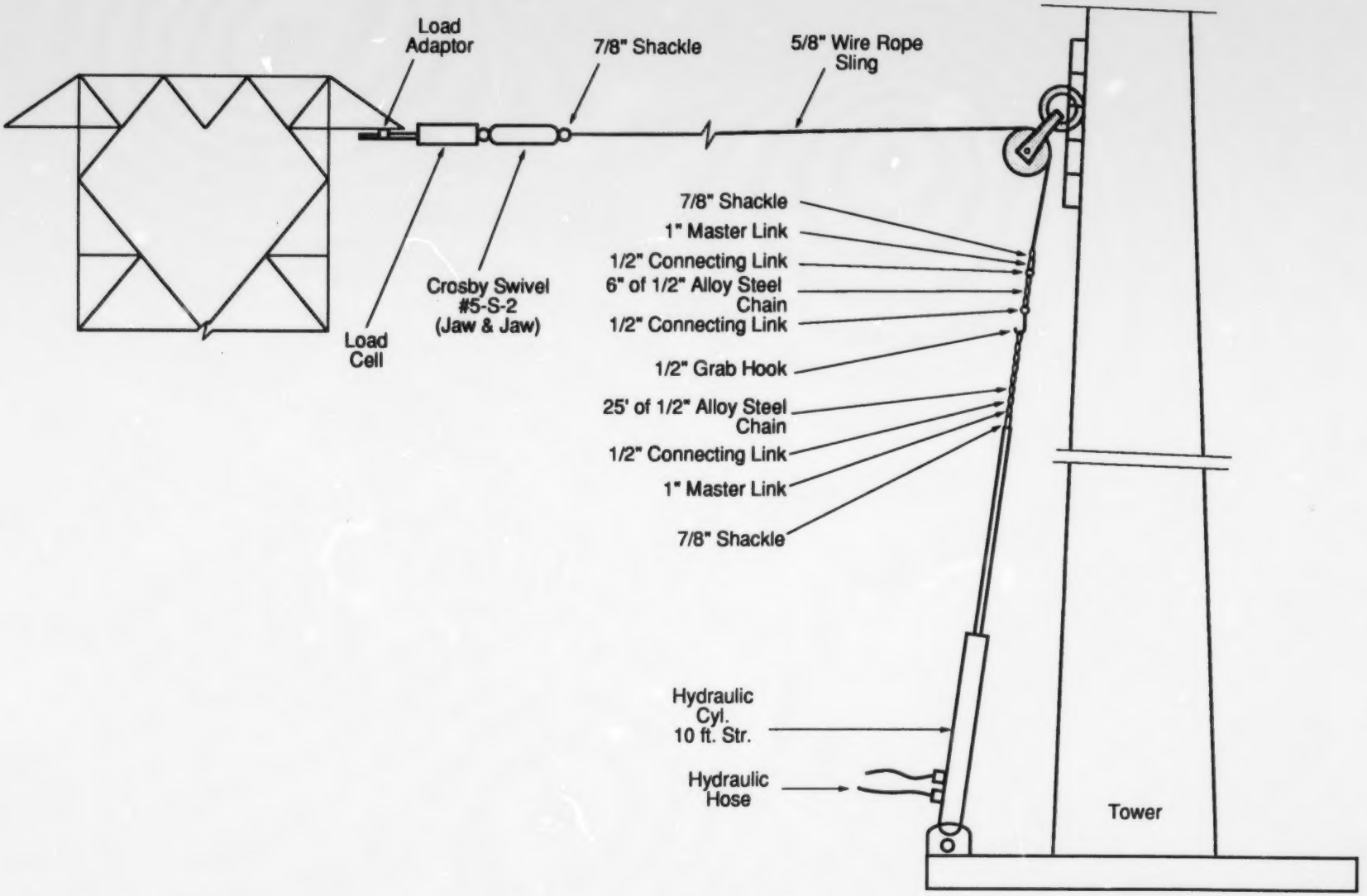


FIGURE 22

TRANSVERSE LOAD RIGGING

89-79
178314-RD
JA 8 DISK

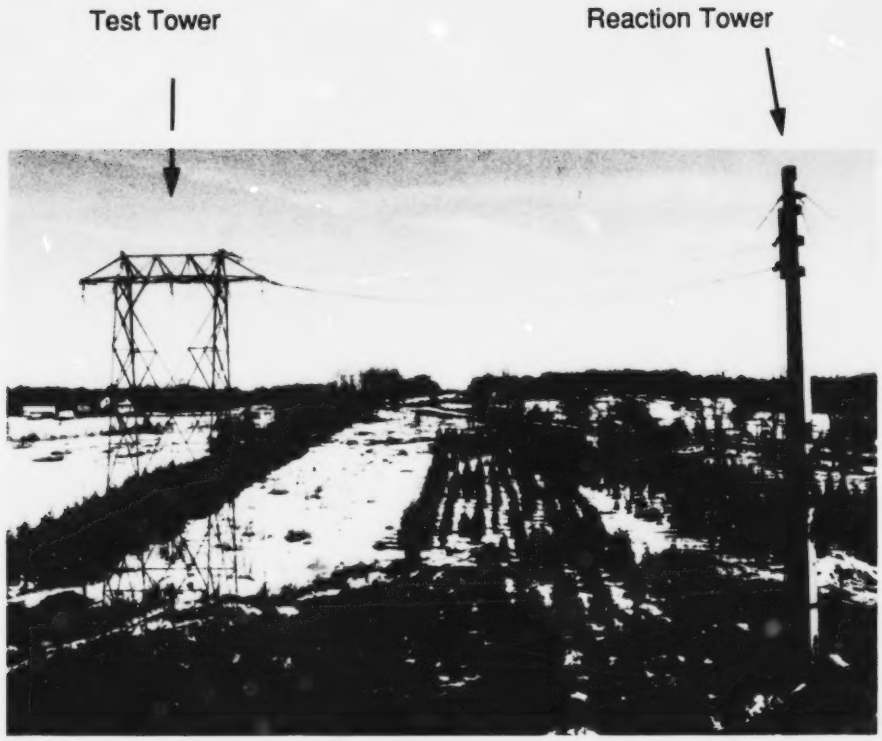


FIGURE 23

APPLYING TRANSVERSE LOADS TO TEST TOWER, TEST B

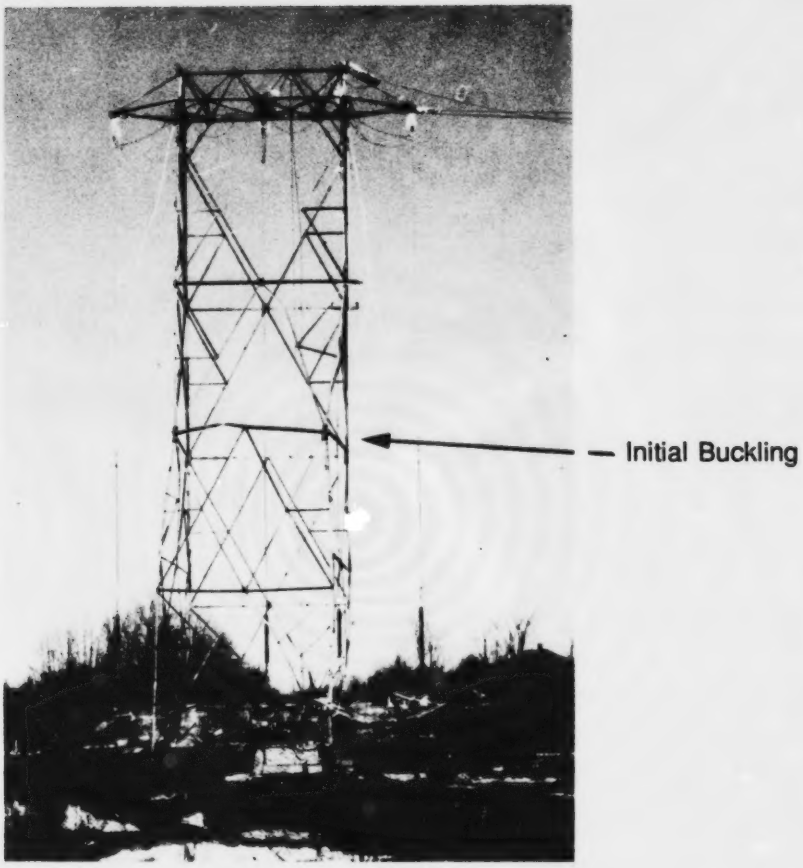


FIGURE 24

TEST B
INITIAL LOCAL FAILURE OF TOWER 66

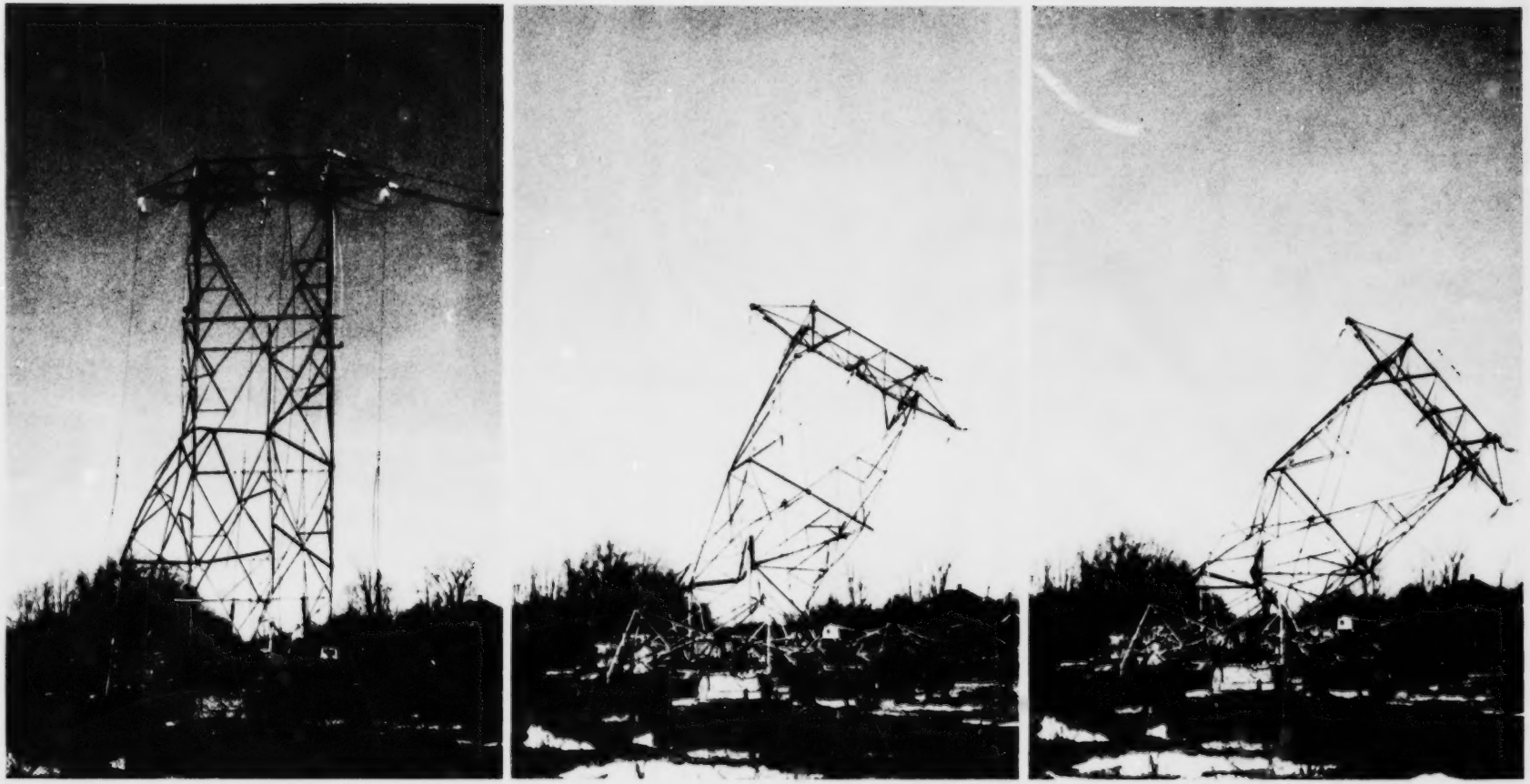


FIGURE 25

VARIOUS STAGES OF TOWER (#66) FAILURE

89-79
178294-RD
BART 4 DISK

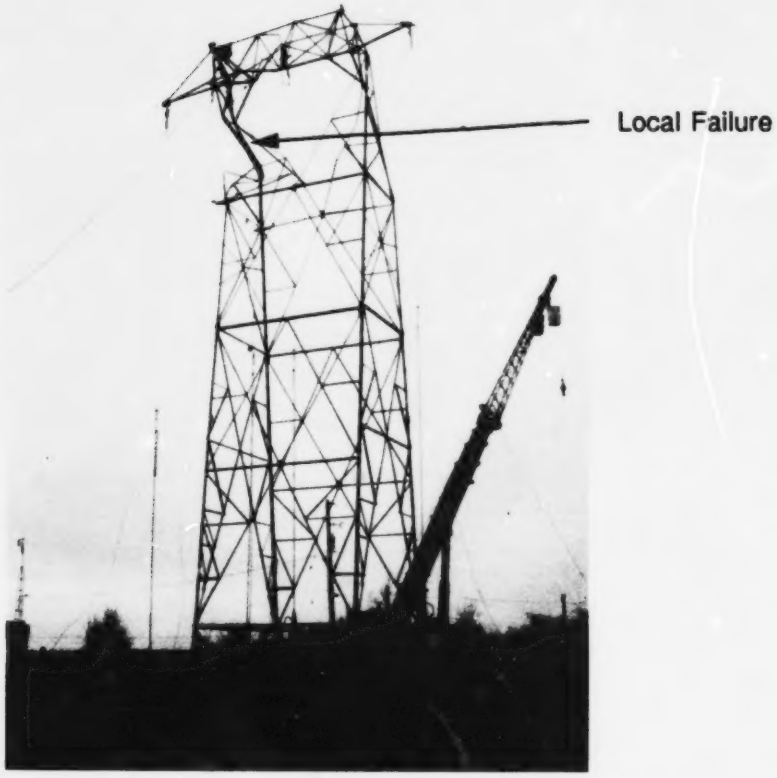


FIGURE 26

LOCAL FAILURE OF TOWER 65

PART II

INSTRUMENTATION, MEASUREMENTS AND DATA ACQUISITION SYSTEM

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R.W. WOLFENDALE AND J. MARSALA

PART II

INSTRUMENTATION, MEASUREMENTS AND DATA ACQUISITION SYSTEM

1.0 INTRODUCTION

This part of the report deals with the type of measuring instruments used in the tower testing, the various measurements done during each tower test and the data acquisition system used to record and store the measured data.

The measuring systems consisted of load cells, strain gauges, linear potentiometer displacement transducers and a weather instrument package. The data acquisition system consists of data loggers, signal conditioners, microcomputers and printers. The information on different instruments used in this project is given in Table I.

2.0 INSTRUMENTATION AND MEASUREMENTS

2.1 Strain in Tower Members

Weldable type strain gauges were used to measure the strain in tower members. Only critical members were instrumented because it was uneconomical to strain gauge every member of the tower. Transmission Line Design Department identified 12 members (Figure 1) on each of the towers 66 and 67 and 15 members on tower 65 to be strain gauged.

Two pairs of strain gauges were spot welded to each critical member as shown in Figures 2a, 2b and 2c. Each pair comprises an axial gauge and a Poisson gauge. The axial gauge measured the axial strain in the member and the Poisson gauge was placed at right angles to the axial gauge to measure the transverse or lateral strain. This strain is related to axial strain through Poisson's ratio which is about 0.3 for steel. It will also measure the component of torsional strains. Effects of load signal wires are balanced. The two gauges were electrically connected to form two adjacent arms of a Wheatstone bridge. All gauges were arranged in this manner resulting in a total of 24 bridges for each of towers 66 and 67 and 30 bridges for tower 65.

The other pair of gauges shown in Figure 2 measures the axial and transverse strains in the other leg of the same member. Differences between the readings of the pairs of gauges would indicate that the member was under bending or torsion.

Strain gauges were also installed on two of the support guywires of the reaction tower. They were used to monitor the tension in these wires as the load was increased during the wind-on-ice load test (i.e., test B).

All strain gauges were protected from moisture by coating them with a wax-based material and a plastic adhesive tape.

2.2 Load Cells

As described in Part I, load cells were used to monitor the loads applied to the tower during the various tests. The details on the location of the load cells and the way they were fastened to the tower are given in Part I.

2.3 Displacement of Foundation and Tower Legs

Civil Research Department was responsible for measuring the movements of the tower foundations. Linear Potentiometer Displacement Transducers (LPDT) and dial gauges were used for this purpose. A photograph of a typical LPDT installation is shown in Figure 3. For tower 66, 12 LPDT's were installed on three of the four foundations. They were oriented to detect movements in the 3 principal directions, X,Y,Z at the anchor bolts and leg joints. The vertical movements of the tower legs were also monitored. The results of this test showed little or no movement of the foundations or the legs. Therefore, tower 67 was instrumented with 9 LPDT's. Monitoring of foundation or leg movements was not done on tower 65.

2.4 Tower Displacement

To measure the deflection of certain points on the tower, mirror targets were installed at each phase and skywire location, at a point about 2/3 up the tower and near the bottom of all four legs. A geodimeter (Figure 4) was used to sight these targets and thus measure tower displacements in three principal directions. The geodimeter was supplied by an Ottawa survey company, Annis, O'Sullivan, Vollebekk Ltd., which was contracted out to carry out the tower displacement measurements. The instrument was stationed approximately 100 feet away from the test towers. The optical instrument contained a computer which on command recorded and stored all the zero readings and calculated the displacements of each load application point. The accuracy of the instrument was reported to be plus or minus 2 mm for all the displacement measurements.

2.5 Weather Data at the Test Site

A portable weather station, installed on a 20 ft. mast, (Figure 5) was located adjacent to the instrument trailer. A 3-cup type sensor was used to measure the wind speed while a wind vane measured the direction. A temperature probe consisting of a thermistor was used to monitor the ambient temperature.

2.6 Miscellaneous Measurements

For the along-the-line tests (ie D1,D2 and D3), a rotary potentiometer was used to monitor the angle of the pulling cable with respect to horizontal. It was located between the load cell and the attachment to the tower. The measured angle was used to calculate the vertical and horizontal components of the applied load.

The surface temperature of one of the tower legs and the air temperature at the instrument trailer were measured using thermocouples.

2.7 Instrument Cables

Each strain gauge circuit was wired using a shielded four conductor Belden (type 8723) instrumentation cable approximately 250 ft long.

3.0 SIGNAL CONDITIONING

Each strain gauge circuit was calibrated in the laboratory by feeding the signal through a 250 ft length of cable into a Vishay P1550A strain calibrator similar to the one used in the field. The calibration was done such that the output was either in microstrains or axial loads or both.

Prior to each test the linear potentiometer displacement transducers were calibrated in-situ using a gauge block of known dimensions and the signals were calibrated to provide the deflections in millimetres.

All calibration procedures were checked thoroughly at every stage of the signal transfer to ensure accuracy. The details on calibration procedures are given in a filing memorandum "Calibration of Instrumentation For Tower Testing at Smiths Falls" dated June 4, 1989, by R. Wolfendale.

4.0 DATA ACQUISITION SYSTEM

A schematic of the instrumentation and data acquisition system used in the tower testing program is shown in Figure 6. Because of the importance placed on obtaining accurate and reliable data, great care was exercised in designing the system and selecting proper instruments and data acquisition hardware.

For this project, two data acquisition systems were employed. One system was designed by the Applied Mechanics Section and the other by the Mechanical Testing and Development Section.

4.1 Primary Data Acquisition System (Applied Mechanics Section)

The primary data acquisition system comprised of a 44 channel Daytronics digital data logger, an IBM-compatible PC and a printer.

The inputs into this system were the signals from 8 of the 24 strain gauge bridges, the linear potentiometer displacement transducers, the angle indicator, the thermocouples, and the anemometer.

The system was programmed to scan the input data at 2, 10, 30 or 60 second intervals. The data was stored on a hard disk at these sampling rates and if a hardcopy was required, the data was sent to the printer. The system was capable of storing a set of calibration factors for converting the measured data, which were in terms of electrical voltages, into engineering units. For example the readings from the strain gauges and the linear potentiometer displacement transducers were converted to microstrains and millimetres, respectively. The wind speed was displayed in metres/second, the wind direction in degrees and all temperature measurements in degrees Celsius.

In addition to these, the strain in the tower legs and in the guys were further reduced to provide the axial load (in pounds) in the respective components.

The time and date were continuously displayed during the test.

4.2 Primary Data Acquisition System (Mechanical Testing Section)

A schematic of the data acquisition system employed by the Mechanical Testing and Development Section to record the signals from load cells and some of the strain gauge bridges is shown in Figure 6. The system was comprised of strain gauge scanners, a voltage scanner and a computer package by Vishay Instruments. The schematic also shows how this system and that used by the Applied Mechanics Section were interfaced to provide simultaneous recordings on both systems.

The inputs to this system were from some of the 12 load cells, which were used to measure the vertical, longitudinal and transverse loads, and from 16 of the total 24 strain gauge bridges on tower members. The system software enabled the operator to scan data at random or at a desired rate and store data on floppy disks as well as directing it to a printer. It also enabled the operator to monitor selected signals in controlling the load increments during tower testing. All load cells including the back up units were calibrated in the laboratory before the tests. The calibration factors were incorporated into the software to convert the electric signals into engineering units. The strain gauge signals were also calibrated in the field prior to testing using a strain calibrator and the calibration factors were used for converting the signals into engineering units.

4.3 Back-up Data Acquisition System (Applied Mechanics Section)

The purpose of the back-up system was to store the key data in case there was a failure in the primary systems. An analog tape recorder was used as a back-up system. Since only 14 channels were available during any test, eight strain gauge signals along with a combination of load, displacement or angle signals were recorded.

TABLE 1

INSTRUMENTATION DETAILS

INSTRUMENT	MANUFACTURER	SPECIFICATIONS
DISPLACEMENT	PENNY & GILES	TYPE: RESISTIVE POTENTIOMETER RANGE: 0 TO 3 INCH LINEARITY: 0.1% OF F.S. SENSITIVITY: 1mV = 0.001 INCH
ANGLE	SCHAEVITZ ACCUSTAR	TYPE: RESISTIVE CLINOMETER RANGE: +/- 45 LINEAR +/- 60 TOTAL DEG. LINEARITY: +/- 1% ANGLE (0.001 DEG.) SENSITIVITY: 1mV = 1 DEGREE
WIND SPEED	GENEQ MODEL W10102	TYPE: PULSE COUNTING GENERATOR RANGE: 0 TO 50 m/s SENSITIVITY: 1mV = 0.001 m/s
WIND DIRECTION	GENEQ MODEL W10202	TYPE: RESISTIVE POTENTIOMETER RANGE: 0 TO 360 DEGREES SENSITIVITY: 1mV = 0.072 DEGREES
AMBIENT TEMPERATURE	GENEQ MODEL T6060	TYPE: THERMISTER RANGE: -50 TO +50 C DEGREES SENSITIVITY: 1mV = 0.02 DEGREES

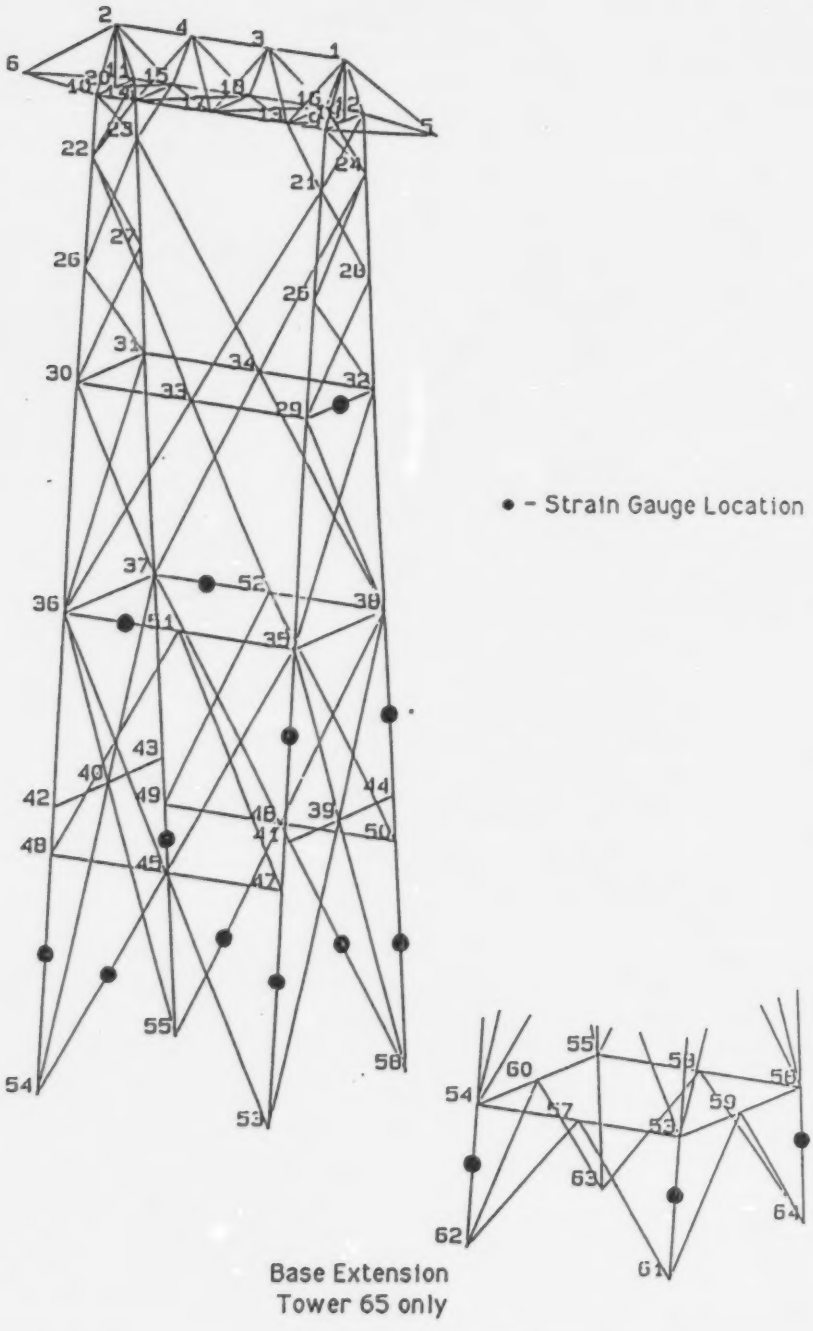
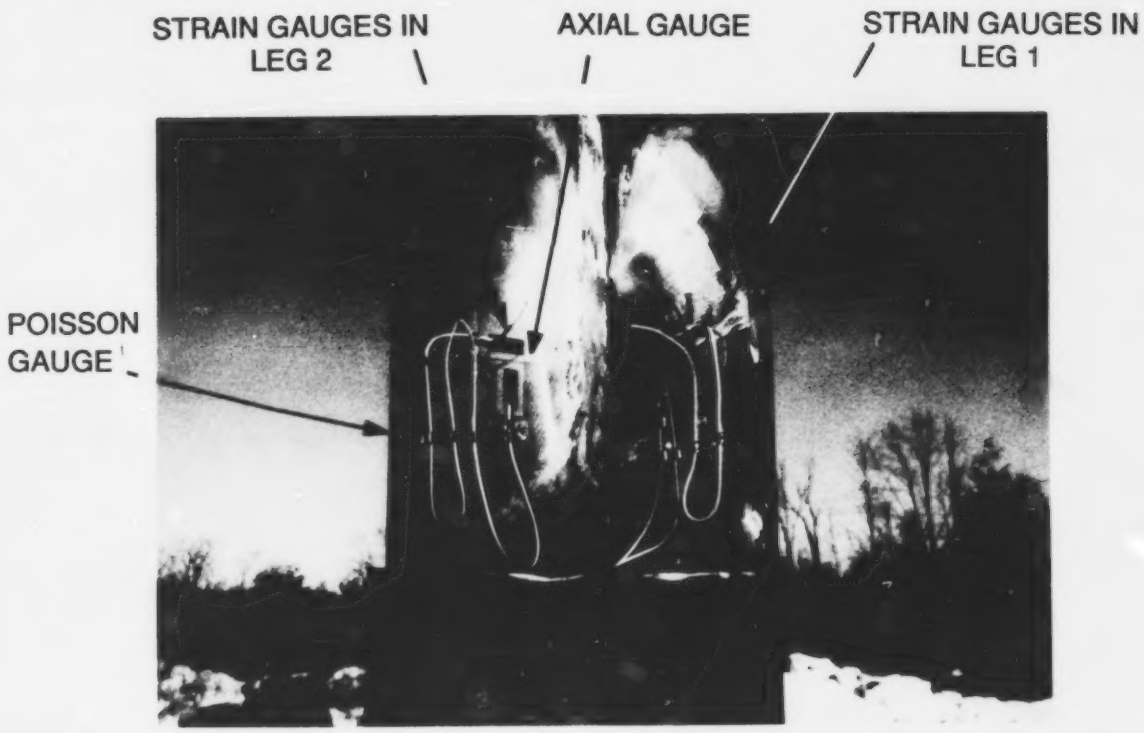
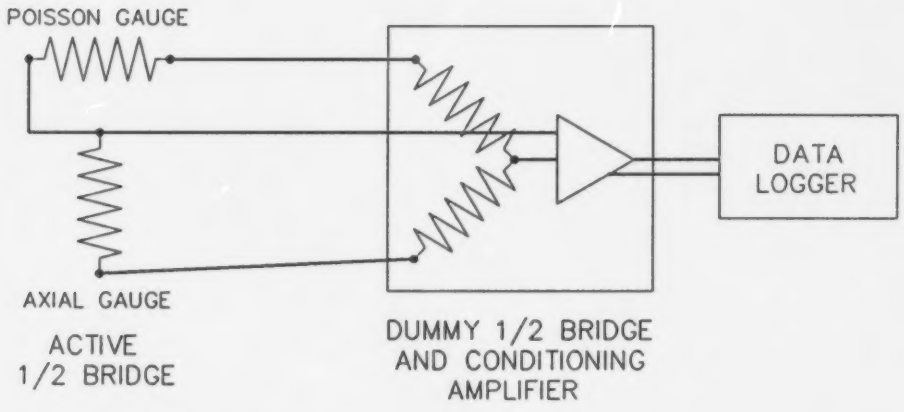


FIGURE 1
LOCATION OF THE STRAIN GAUGED MEMBERS



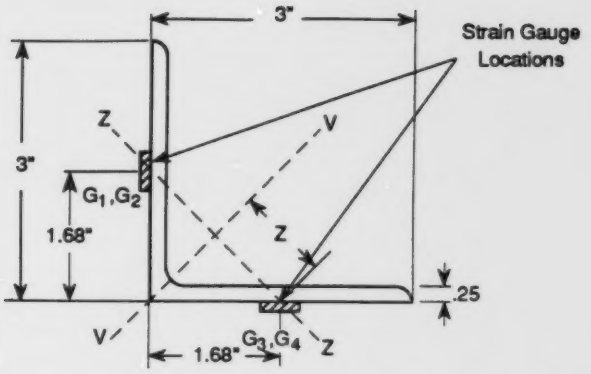
a) STRAIN GAUGE ON A TYPICAL TOWER MEMBER



b) SCHEMATIC DIAGRAM OF ELECTRICAL CONFIGURATION

FIGURE 2

TYPICAL STRAIN GAUGE INSTALLATION



At Gauge Locations

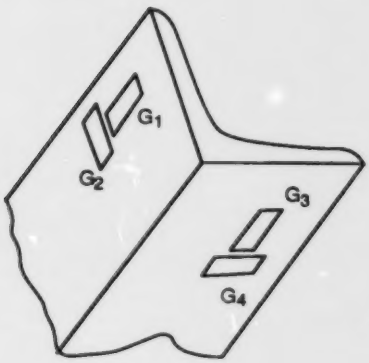
$$\sigma = \frac{P}{A} + \frac{M_Z Z}{I_Z}$$

or $$\varepsilon_Z^+ = \frac{P}{AE} + \frac{M_Z Z}{I_Z E}$$

$$\varepsilon_Z^- = \frac{P}{AE} - \frac{M_Z Z}{I_Z E}$$

Where

VV = a principle axis
ZZ = a principle axis
P = axial load
A = cross-sectional area
I_Z = moment of inertia about ZZ
σ = stress
ε = strain in axial direction
E = modules of elasticity
M_Z = moment about ZZ axis



c) Example of strain gauge locations on a typical angle member.

FIGURE 2

TYPICAL STRAIN GAUGE INSTALLATION

FIGURE 3

PHOTOGRAPH OF A TYPICAL INSTALLATION OF LINEAR POSITION TRANSDUCERS

Geodimeter

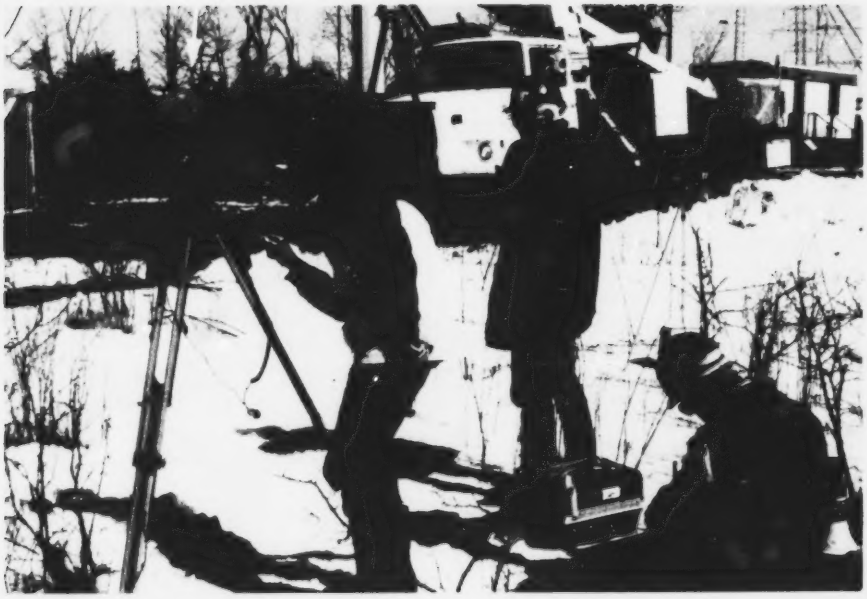


FIGURE 4

GEODIMETER USED IN MEASURING TOWER DISPLACEMENT

179300-K3-RD
89-79

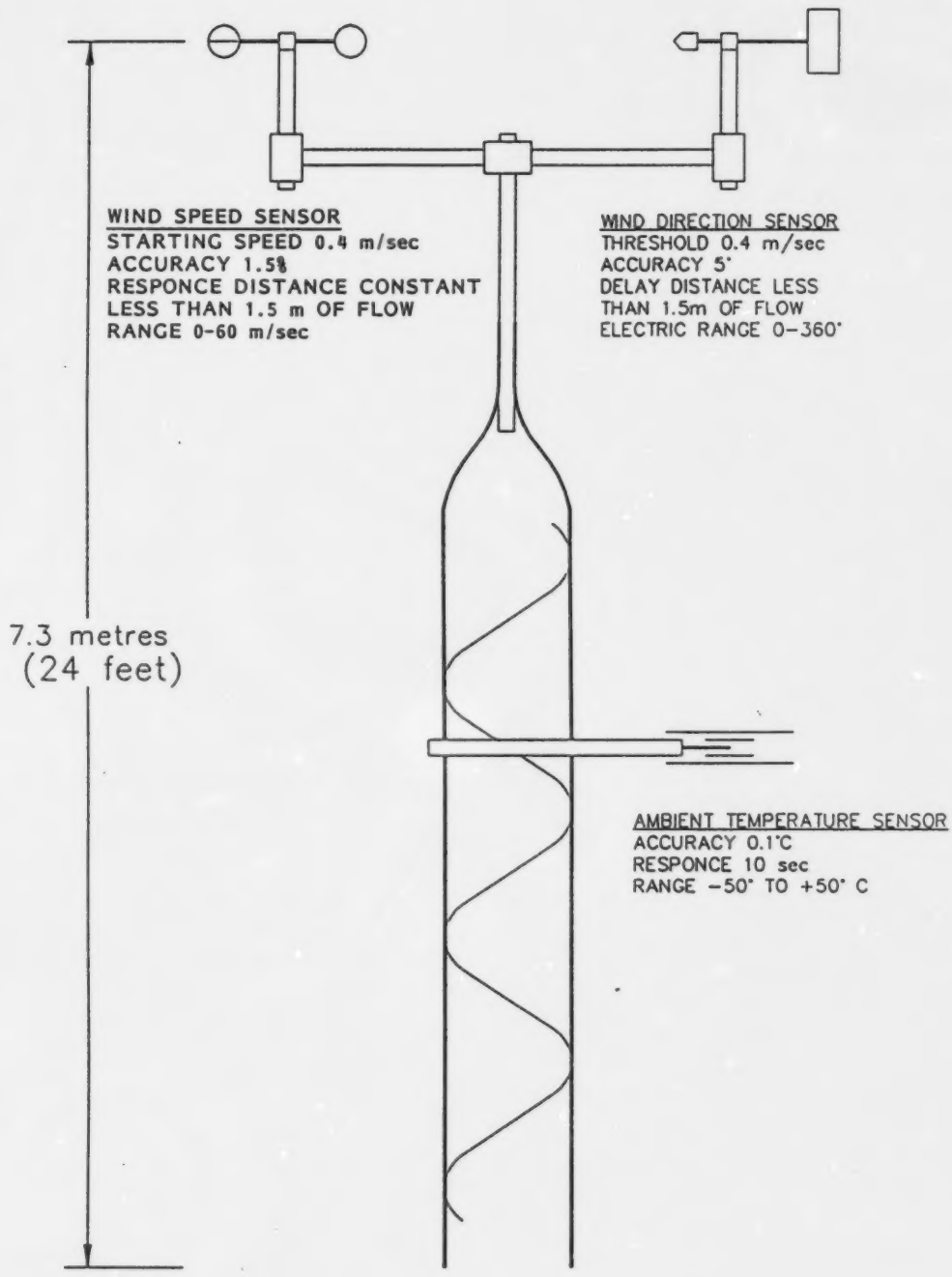


FIGURE 5

INSTRUMENTATION FOR WEATHER DATA

89-79
179298-RD

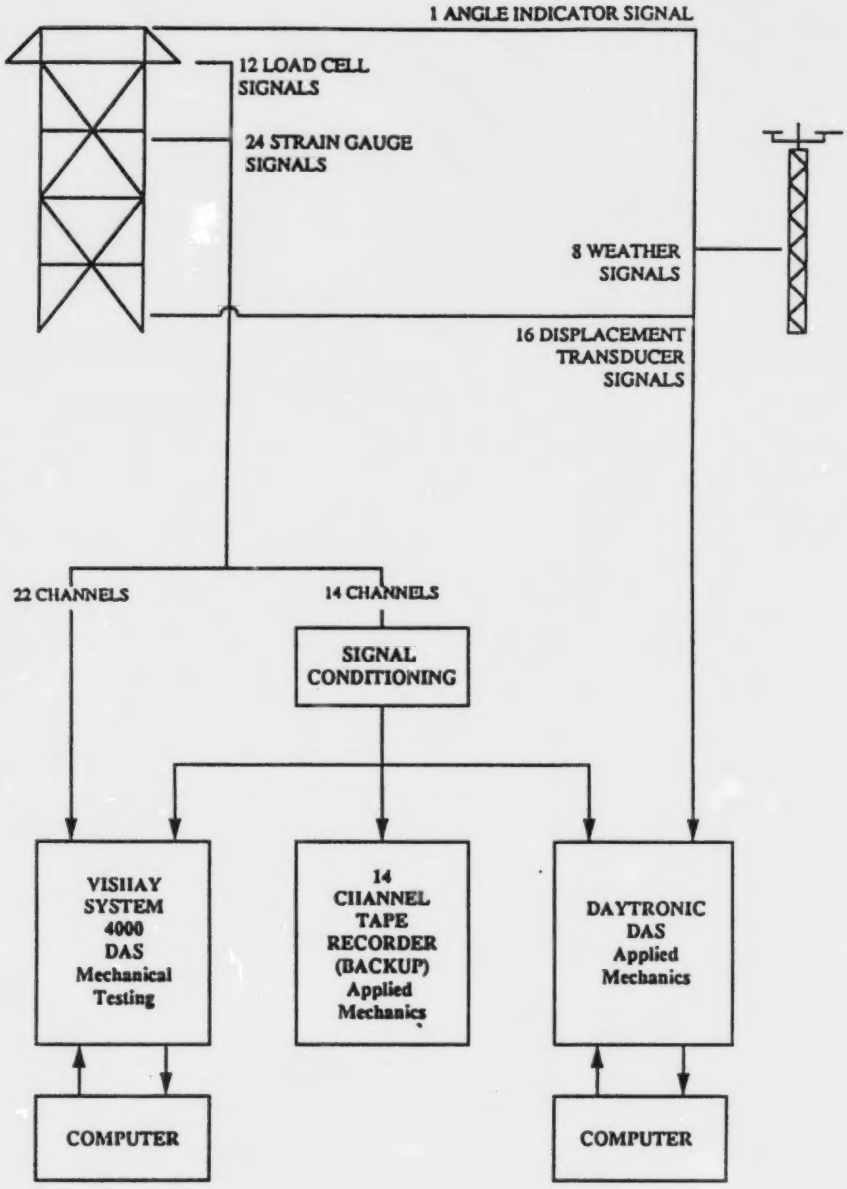


FIGURE 6

DATA ACQUISION SYSTEM FOR THE TOWER TESTING PROGRAM

PART III

DATA ANALYSIS AND DISCUSSION

S.G. KRISHNASAMY, M. TABATABAI AND H.S.RADHAKRISHNA

PART III

DATA ANALYSIS AND DISCUSSION

1.0 INTRODUCTION

In this section of the report the information gathered from the tower testing program is presented along with some selected data analysis. Some typical test measurements are compared with corresponding values predicted by the Transmission Line Design Department.

2.0 MEASURED DATA

In order to evaluate the behaviour of the foundation and tower structure under the various applied load conditions, a number of important parameters (Figure 1) such as strains in the members, foundation displacements and tower deflections were measured. Detailed descriptions of the input loads, the measured parameters, the measuring instruments and the data acquisition system are provided in Parts I and II of this report.

2.1 Typical Sets of Data

Typical sets of data gathered from the tests on towers 66 and 67 are given in Tables 1 and 2, respectively. The data on towers 66 and 67 include the applied loads, strains in selected tower members, displacement of foundation and tower joints, wind speed, wind direction and ambient temperature. Since the structural configuration of towers 66 and 67 and the applied loads on them are similar, the type of data obtained from tests on these towers also should be similar.

However, the structural configuration of tower 65 (Figure 1, Part II) was slightly different than that of towers 66 and 67 and it was subjected to longitudinal loading only. Therefore, the number and the type of members strain gauged on tower 65 was also different. Typical information on applied loads, strains in structural members and deflections for tower 65 are given in Table 3.

3.0 DATA ANALYSIS

The Information gathered from the various types of tests done on towers 65, 66 and 67 could be used to perform the following analyses:

- Compare the predicted and actual tower failure loads.
- Compare the calculated and measured deflections of tower joints.
- Study the foundation deflections under the various applied loading conditions.
- Analyse the load distribution in the instrumented tower members.
- Assess the reserve strength available for refurbishing.
- Study in detail the calculated and measured loads on typical tower members (this analysis will be done later in a separate report).

3.1 Loading Sequence

As pointed out in Part I of this report the loading sequence on each tower was such that it would fail under the last load type applied. For example, towers 66 and 67 were loaded in the following sequence and they would fail under the wind-on-ice load condition:

- Heavy ice
- Broken skywire
- Broken outer conductor
- Broken centre conductor
- Heavy ice and strong wind or wind-on-ice (tower was loaded to failure under this loading)

Tower 65 would be subjected to the following loading sequence and would fail under the broken outer conductor loading condition :

- Heavy ice
- Broken skywire (tower prematurely failed under this loading)
- Broken outer conductor

3.2 Comparison of Actual and Predicted Tower Failure Loads

The predicted and the actual failure loads for all the three towers are listed in Table 4. In general the predicted failure loads were close to the actual ones and the difference between the two ranged from 1%-9%. As planned, the towers 66 and 67 failed under the wind-on-ice load condition. However, tower 65 prematurely failed under the broken skywire load condition even though it was originally planned to fail it under the broken outer conductor load condition. The probable reason for the premature failure is the excessive axial compressive load resulted from the vertical component of the along-the-line load cable. This load component was not originally considered in the analysis. The tests also show that the towers have reserve strength of about 50 percent of the loads applied in service. This reserve strength can be utilized for upgrading the conductor on this line.

3.3 Comparison of Measured and Predicted Tower Deflections

In Table 5 some typical measured tower deflections just prior to failure are listed along with the corresponding calculated values. The measured deflections for towers 66 and 67 ranged from 2.2 to 5.8 inches. As expected the maximum deflection was at the conductor attachment point and occurred under the maximum wind-on-ice loading. The correlation between the measured and the predicted deflections was not as close as it was between the actual and predicted failure loads. The difference between the measured and predicted deflections ranged from 30% to 90%. Since the loading condition on tower 65 was limited to along the line load only, the maximum deflection was about 4.4 inch in the longitudinal direction. The difference between the measured and the predicted deflections ranged from 6% to 50%. The major reason for the large discrepancies between the measured and predicted deflections could be attributed to bolt slippage and possible local yielding.

3.4 Comparison of Measured and Predicted Tower Member Loads

As indicated earlier, several important members of each tower were instrumented to assess the loads carried by them during various tests. The strain gauge instrumentation design was based on the assumption that the loads on the members will be mainly axial. As indicated in Part II of this report, both legs of each member were identically strain gauged to find out whether or not it was subjected to any non-axial loading. If the two strains readings are of different sign (e.g., compression in one leg and tension in the other leg) it would mean the member was subjected to a loading other than axial. The information on strain values could be used to assess qualitatively the degree of non-axial loading on tower members. As shown in Figure 2(c) of Part II the sum of the strains in both legs of a member will be equal to the axial strain which in turn can be converted into axial load as shown in Tables 6,7 and 8. It is assumed here that the distorsion of the member due to non-axial loading is relatively small.

Tables 6 to 8 contain the measured loads on each of the instrumented members just prior to failure. These loads were calculated from the measured strains by applying the appropriate member and material properties given in Tables 9 and 10. As seen from Tables 6, 7 and 8, only members subjected to axial loads above 10 percent of their yield or buckling strength were considered in the analysis. Also, the members that were subjected to relatively excessive bending or torsion (eg. members 29-32, 37-52, 36-51 and 46-56 in Table 8) were omitted from the analysis. It also should be pointed out that since no measurements were made on both legs of the vertical members (Table 6) 39-53, 56-64, 53-61, 54-62 and 55-63 during tests on Tower 65, it was assumed that the strains in both legs would be the same. Since the vertical members in general experience relatively little distorsion (eg. members 38-44 and 50-56) this assumption should not introduce any significant error in the load.

The measured axial loads on members just prior to failure are correlated with the corresponding calculated values (Table 6, 7 and 8) and the correlation plots are shown in Figures 2 to 4. Also included in Tables 6-8 are the percentage ratio between the load on each member and its load carrying capacity. These ratios show the extent to which the members were loaded with respect to their load carrying capacity.

Considering the assumptions involved both in the calculations and in the experimental procedure and the structural and loading asymmetry, the extent of correlation seen in Tables 6-8 and Figures 2-4 is fairly satisfactory. A linear elastic analysis was used in calculating the member loads. In general the measured values of loads on individual members were slightly lower than the predicted ones.

A detailed analysis of the measured values and their correlation with corresponding predicted values will be done later in a separate report.

3.5 Study of Foundation Loads

The loads transmitted to the foundation during the tower tests were calculated from the measured loads on the main leg member and one of the two diagonals. The load transfer to the foundations was estimated from a space frame analysis of the tower modelled with pin joints and fixed supports. Table 11 shows the foundation reaction values, both measured and calculated, for the wind-on-ice load (step B-12) on tower 67.

Good agreement was observed between the measured and estimated values of the foundation loads for the uplift legs. For the compression legs, the measured loads are about 20 to 30 percent smaller than the calculated values. The measured loads are based on only axial strains of the main leg member and one of two diagonals. This may account for the discrepancy between the measured and estimated reaction forces.

3.6 Study of Foundation Displacements

The deflection of the legs at the ground level were negligible up to the tower failure. The rock anchors of similar type tested at tower 145 failed by the rod yielding under a load of 30 Kips per anchor. Each tower leg foundation consisted of two rock anchors at tower 145.

Assuming that the rock anchors for tower 67 had similar strength (i.e., 30 Kips/anchor), the maximum load transmitted to footings in uplift was only about 33% of the ultimate capacity. Thus the rock anchored footings were more than adequate for the anticipated loads.

3.7 Study of Grillage Foundation

The measured loads for tower 67 have been used to predict some of the grillage foundations responses at other site conditions (Research Report 88-183-K.)[1] If the footings for tower 67 were of steel grillage type with their sizes and soil conditions similar to tower 84, then the uplift legs would have lifted up by one-half inch under the maximum applied load of 19 Kips per leg in the tower test.

However, if the footings at tower 67 were similar to tower 143, whose ultimate uplifting capacity was 12 Kips per leg, then the tower would have toppled by the pull out of the uplift legs before the maximum applied tower load was reached.

The large variation in uplift capacity of footings between Towers 84 and 143 was the result of variabilities in soil/backfill conditions and in the structural details of the grillage pads.

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1. R. Tsang and H.S. Radhakrishna, Transmission Line Refurbishment Study, Tower Foundation Inspection and Testing. Smith Falls to Kingston 115 KV TL, CCT S1K. R.Report 88-183-K, Nov.1988.

The strength of grillage type tower footings can vary widely for a given line depending on the soil and backfill conditions, while the integrity of tower leg and footing depends upon the soil corrosivity and age. Therefore, the tower line refurbishment programs should include a survey of the soil conditions for both their strength and corrosivity.

4.0 CONCLUSIONS

The analyses of the data gathered from the tower tests have led to the following conclusions:

- The correlation is good between the predicted and actual tower failure loads.
- There is sufficient reserve strength available in the tower for upgrading the conductor on this line.
- The extent of correlation is satisfactory between the calculated and measured tower member loads.
- In general the measured member loads were slightly lower than the calculated values.
- The agreement is good between the measured and estimated values of foundation loads.
- The rock-anchor foundation did not show any movement at all.
- In general the extent of correlation between the predicted and measured deflections of joints was fair.

5.0 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance provided by the following staff during the various stages of the tower testing program; Mr. M. Kastelein, Mr. E. Stasiuk, Mr. W. Eyles, Mr. N. Miura, Mr. J. Kalnins, Mr. J. Gifford, Mr. D. Mitchell, Mr. D. Austin, Mr. D. King and the construction staff at Pickering G.S. The authors also acknowledge the assistance provided by Mr. B. W. Warkentin in the compilation of this report.

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TABLE 1

TYPICAL DATA OBTAINED FROM TESTS ON TOWER 66

	Parameter Recorded	Loading Type	Heavy Ice (A-6)		Broken Skywire (D1-2)		Broken Outer Conductor (D2-2)		Broken Centre Conductor (D3-2)		Wind-On-Ice Load (B-7)	
APPLIED VALUES	Vertical load on joints(lbs):	1	2862		2522		2523		2523		2479	
		6	2625		2295		2295		2294		2307	
		17&18	2676		2316		2310		2298		2301	
		5	2609		2304		2300		2392		2336	
	Along the line load[1] on joints (lbs):	1			1913							
		5					1886					
		17&18							2003			
	Across the line load[1] on joints (lbs):	1									1405	
		6									2006	
		17&18									1969	
		5									2032	
MEASURED VALUES	STRAIN (10^{-6} in/in) IN MEMBERS: (See Figure 1, Part II)		Leg1*	Leg2*	Leg1	Leg2	Leg 1	Leg 2	Leg 1	Leg 2	Leg 1	Leg 2
		29-32	5.5	11	-4.3	13	-42	1	1.2	10	29	2
		37-52	-6.7	-9	44	7	15	8	25	8	-3	-14
		36-51	1.8	10	-12	6	-24	-15	-18	6	-106	13
		38-44	-63	-50	-173	-159	172	-157	-125	-115	-285	-270
		35-41	-63	-43	48	43	25	16	10	9	-239	-255
		50-56	-44	-64	-158	-160	-138	-172	-113	-117	-306	-270
		47-53	-75	-52	56	34	25	11	13	6	-241	-313
		48-54	-34	-31	0	0	26	-16	30	32	151	111
		49-55	-26	-44	-55	-56	-67	-45	-85	-89	198	201
		45-54	-20	-22	47	27	103	76	18	7	357	311
		46-55	-33	-16	-128	-30	-175	-24	-76	-3	317	195
		46-56	-33	-24	-38	-16	30	37	-53	-44	-480	-156

* See Fig.1 in Part II of the report. (+) tension; (-) compression.
1 The along the line load was applied at an angle.
2 The angle of along the line load w.r.t. horizontal axis.
3 Clockwise with respect to North.

TABLE 1 (Cont.)

TYPICAL DATA OBTAINED FROM TESTS ON TOWER 66

	Parameter Recorded	Loading Type	Heavy Ice (A-6)			Broken Skywire (D1-2)			Broken Outer Conductor (D2-2)			Broken Centre Conductor (D3-2)			Wind-On-Ice Load B-7		
			X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
MEASURED VALUES	DEFLECTION (mm) OF TOWER AT JOINTS: (See Figure 1, Part II)	56	-3	0	0	-1	-2	2	0	-3	-1	2	1	0	8	-1	0
		53	0	1	0	-2	0	-1	-1	-1	2	0	0	1	5	-3	0
		54	-4	3	0	-1	-2	1	0	-2	0	0	0	-1	9	-3	4
		55	-2	0	0	-1	0	2	-2	-2	1	1	2	-1	6	-3	3
		T2	4	-5	0	-1	0	15	1	-5	17	2	-6	1	74	-13	2
		T3	0	-18	3	0	-7	4	0	-8	-3	2	-7	11	58	-1	-4
		T4	0	-5	1	-4	-3	8	1	-4	8	0	-4	10	57	-22	-12
		T5	-1	-16	2	-3	-7	16	-5	-16	28	0	-12	9	55	-34	1
		T6	na	na	na	-1	-1	8	1	-3	9	0	0	5	34	-7	4
	FOUNDATION DISPLACEMENT (mm) AT LOCATIONS: (See Figure 1, Part II)	D1		0			0			0			0			0	
		D2		0			0			0			0			-1	
		D3		0			0			0			0			-1	
		D4		0			-1			0			0			-2	
		D5		0			0			0			0			0	
		D6		0			0			0			0			0	
		D7		0			0			0			0			-1	
		D8		0			0			0			0			0	
		D9		0			-1			0			0			0	
		D10		0			0			0			0			0	
		D11		0			0			0							
		D12		0			0			0							
		D13		0			0			0							
		D14		0			0			0							
		D15		0			0			0							
		D16		1			0			0							
		D17		0			0			0							
		D18		0			0			0							
		D19		0			0			0							
		D20		0			-1			0							
MISC.	Angle(°)[2]			0			15			14			13			0	
	Temperature(C°)			8.5			9.5			3.1			3			1	
	Wind speed(m/s)			---			3			2			2			2	
	Wind direction[3]			---			350			210			230			-130	

X - Across the line direction
Y - Vertical direction
Z - Along the line direction

TABLE 2

TYPICAL DATA OBTAINED FROM TESTS ON TOWER 67

	Parameter Recorded	Loading Type	Heavy Ice (A-6)	Broken Skywire (D1-2)	Broken Outer Conductor (D2-2)	Broken Center Conductor (D3-2)	Wind-On-Ice Load (B-7)
APPLIED VALUES	Vertical load on joints(lbs):	1	2899	2517	2521	2520	2516
		6	2691	2293	2276	2276	2269
		17&18	2673	2297	2306	2299	2261
		5	2640	2394	2366	2357	2380
	Along the line load[1] on joints (lbs):	1		2056			
		5			2073		
		17&18				3818	
	Across the line load[1] on joints (lbs):	1					1572
		6					2048
		17&18					2056
		5					2076

MEASURED VALUES — STRAIN (10^{-6} IN/IN) IN MEMBERS: (See Figure 1, Part II)	Leg1*	Leg2*	Leg1	Leg2	Leg 1	Leg 2	Leg 1	Leg 2	Leg 1	Leg 2
29-32	18.9	4	12.8	18	17.7	0	-5.5	21	9.8	-9
37-52	3.7	1	18.9	20	17.1	-21	29.9	-6	-131	-4
36-51	8.5	1	-9.2	-2	1.8	8	-23.	8	-118	-9
38-44	-70.	-72	-161	-156	-61	-60	-164	-197	-265	-256
35-41	-43.	-45	59.2	44	1.2	32	99.5	127	-290	-245
50-56	-48.	-74	-152	-154	-59.	-70	-153	-197	-262	-314
47-53	-39.	-45	50.7	39	12.2	37	111.	131	-325	-281
48-54	-4.9	-39	19.5	13	50.7	7	66.5	16	211	193
49-55	-38	-33	-74	-65	-153	-121	-147	-109	140	150
45-54	-27	-23	59	45	-124	-98	-36	-39	384	367
46-55	-39	-23	-142	-73	70	50	-68	-47	362	325

* See Fig.1 in Part II of the report. (+) tension; (-) compression.
1 The along the line load was applied at an angle
2 The angle of along the line load w.r.t. horizontal axis
3 Clockwise with respect to North

TABLE 2 (Cont.)

TYPICAL DATA OBTAINED FROM TESTS ON TOWER 67

	Parameter Recorded	Loading Type	Heavy Ice (A-6)			Broken Skywire (D1-2)			Broken Outer Conductor (D2-2)			Broken Center Conductor (D3-2)			Wind-On-Ice Load B-7		
			X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
MEASURED VALUES	DEFLECTION (mm) OF TOWER AT JOINTS: (See Figure 1, Part II)	56	0	1	-1	0	-3	2	2	-1	-1	0	0	-1	3	-3	-29
		53	-2	2	1	1	-2	1	-1	-2	0	-2	1	2	7	-1	-7
		54	1	-2	-2	1	-2	0	-2	0	2	-1	0	-1	6	0	1
		55	-1	-1	-3	0	-3	1	1	-3	-4	-1	-1	1	6	0	-5
		T2	8	-6	1	1	-4	17	-8	-2	19	-6	0	17	69	-10	-8
		T3	1	-9	0	3	-8	4	-2	-10	27	-2	-6	16	59	3	6
		T4	-3	-7	0	3	-6	10	-3	-3	11	-1	-3	19	64	-8	-3
		T5	1	-15	6	4	-8	18	-2	-15	0	-2	-14	18	[illegible]	-25	-8
		T6				3	-2	8	-3	0	9	-1	1	10	[illegible]	-13	-4
	FOUNDATION DISPLACEMENT (mm) AT LOCATIONS: (See Figure 1, Part II)	D1	-2			3			0			-1			0		
		D2	0			0			0			0			0		
		D3	0			0			0			0			0		
		D4	0			0			-1			0			1		
		D5	0			0			-1			0			0		
		D6	0			0			-1			0			0		
		D7	0			0			-1			0			-3		
		D8	0			0			-1			0			0		
		D9	0			0			-1			0			0		
		D10	0			-1			-1			-1			3		
MISC.	Angle(°)[2]		0			17			16			13			0		
	Temperature(C°)		12			15			13			13			7		
	Wind speed(m/s)		4			3			2			3			2		
	Wind direction[3]		64			117			37			69			250		

X - Across the line direction
Y - Vertical direction
Z - Along the line direction

TABLE 3

TYPICAL DATA OBTAINED FROM TESTS ON TOWER 65

	Paramters Recorded	Loading Type	Heavy Ice (A-3)		Broken Skywire Wire (D1-2)	
APPLIED VALUES	Vertical load on joints (lbs)	1	2453		2497	
		6	2262		2329	
		17&18	2210		2279	
		5	2265		2301	
	Along the line load[1] on joints (lbs):	1			1934	
		5				
		17&18				
	Across the line load[1] on joints (lbs):	1			1849	
		6				
		17&18				
		5			3062	
MEASURED VALUES	STRAIN (10^{-6} IN/IN) IN MEMBERS: (See Figure 1, Part II)		Leg 1*	Leg 2*	Leg 1*	Leg 2*
		29-32	16.5	9	-9.8	6
		32-55	9.8	-20	-14.6	73
		35-38	19.5	9	9.8	1
		38-44	-51.3	-46	-152	-150
		30-31	11.6	5	7.9	-3
		50-56	-49.4	-48	-158.	-143
		36-37	8.5	10	9.2	-3
		36-51	12.2	8	-8.5	4
		47-53	-52.5	-39	33.6	26
		37-43	-6.1	-23	-59.2	-67
		39-53		-19		13
		56-64		-63		-159
		53-61		-51		33
		54-62		-44		18
		55-63		-30		-89

* See Fig.1 in Part II of the report.
(+) tension; (-) compression.

1 The along the line load was applied at an angle

2 The angle of along the line load w.r.t. horizontal axis

3 Clockwise with respect to North

TABLE 3 (Cont.)

TYPICAL DATA OBTAINED FROM TESTS ON TOWER 65

	Parameters Recorded	Loading Type	Heavy Ice (A-3)			Broken Skywire Wire (D1-2)		
			X	Y	Z	X	Y	Z
MEASURED VALUES	DEFLECTION (mm) OF TOWER AT JOINTS: (See Figure 1, Part II)	64	-7	1	0	1	-2	-2
		61	-12	-4	0	-3	-5	-1
		62	-8	-1	-1	2	0	1
		60	-8	-2	1	-2	0	2
		T2	-4	-2	0	-2	-2	17
		T3	-1	-9	0	-4	-7	1
		T4	-2	2	-1	-1	-8	9
		T5	-5	-5	0	1	-5	19
		T6				-1	-3	9
	FOUNDATION DISPLACEMENT (mm) AT LOCATIONS: (See Figure 1, Part II)	D1	0			0		
		D2	0			0		
		D3	0			0		
		D4	0			0		
		D5	0			0		
		D6	0			0		
		D7	0			0		
		D8	0			0		
		D9	0			0		
		D10	0			0		
MISC.	Angle(°)[2]		0			17		
	Temperature		11			7		
	Wind speed		2			5		
	Wind direction[3]		335			200		

X - Across the line direction
Y - Vertical direction
Z - Along the line direction

TABLE 4

ACTUAL AND PREDICTED FAILURE LOADS ON TOWERS 65, 66 AND 67

TOWER NO.	LOADING TYPE	LOADING+ JOINT	DESIGN LOAD (lbs)	ACTUAL LOAD (lbs)	PREDICTED LOAD (lbs)	DIFFERENCE (%)	REMARK
66	Wind-on-ice load (Transverse)	1	1500	220*	2100	-	(1)
		6	2000	3000	2800	7.1	
		17&18	2000	2980	2800	6.5	
		5	2000	3020	2800	7.9	
67	Wind-on-ice load (Transverse)	1	1500	2200	2100	4.8	(1)
		6	2000	2830	2800	1.1	
		17&18	2000	2960	2800	5.7	
		5	2000	2890	2800	3.2	
65	Broken skywire load (Along-the-line)	1	4000	7200	7800	- 8.3	(1) & (2)

* The loading joint failed before the tower

(1) A total vertical load of about 9000 lbs was applied to the tower in both the measurement and the analysis.

(2) An additional vertical load of about 1500 lbs (the vertical component of the applied along-the-line load) was present just prior to failure.

% Difference = 100 x (Measured - Predicted) / Predicted

TABLE 5

COMPARISON OF MEASURED AND PREDICTED
DEFLECTIONS AT SELECTED JOINTS JUST PRIOR TO FAILURE

JOINT NO.	TOWER 65 ALONG THE LINE DEFLECTION (IN) MEAS.	PRED.	% DIFF.	TOWER 66 ACROSS THE LINE DEFLECTION (IN) MEAS.	PRED.	% DIFF.	TOWER 67 ACROSS THE LINE DEFLECTION (IN) MEAS.	PRED.	% DIFF.
1	4.4	2.9	52	4.1	2.8	46	5.8	3.3	78
6	-0.1	0.1	--	3.7	2.7	37	5.3	3.2	66
17	1.9	1.8	6	3.5	2.7	30	5.7	3.1	84
5	4.1	3.3	24	3.4	2.7	26	5.6	3.1	81
29	2.1	1.7	24	2.2	5.5	-60	3.6	5.8	-38

% Difference = 100 x (Measured - Predicted) / Predicted

NOTE: Along the line deflection = longitudinal deflection
Across the line deflection = transverse deflection

TABLE 6

COMPARISON OF MEASURED AND PREDICTED LOADS* IN MEMBERS JUST PRIOR TO FAILURE - TOWER 65

TOWER FAILED DUE TO BROKEN SK[illegible]URE LOAD

MEMBER		MEASURED LOAD (LBS)		TYPE OF PRE-DOMINANT LOAD IN MEMBER +	AVG. LOAD ON MEMBER (LBS)		%	RATIO OF MEASURED TO YIELD OR BUCKLING LOAD (%)	COMMENTS#
No.	TYPE	LEG 1	LEG 2		MEAS.	PRED.	DIFF.		
29-32	Horiz.	-580	301	T or B	-279	-1679	---	--	E.D.
32-35	Diag.	-142	3111	T or B	2969	5283	---	--	E.D.
35-38	Horiz.	-683	-87	T or B	-770	-2502	---	--	L.L.,E.D.
38-44	Vert.	-10286	-10811	A	-21097	-27663	-24	73	
30-31	Horiz.	7	-21	I	-14	266	---	--	L.L.
50-56	Vert.	-10286	-11691	A	-21977	-27889	-21	59	
36-37	Horiz.	49	-136	T or B	-87	174	---	--	L.L.
36-51	Horiz.	-690	-64	T or B	-754	-1847	---	--	L.L.,E.D.
47-53	Vert.	6473	5028	A	11501	11336	1	20	
37-43	Vert.	-4378	-4840	A	-9218	-11870	-22	32	
39-53	Diag.		1289	T or B	2578^	4902	---	--	
56-64	Vert.		-10789	A	-21578^	-24729	-13	59	
53-61	Vert.		7668	A	15336^	15351	0	27	
54-62	Vert.		4106	A	8212^	6553	25	14	
55-63	Vert.		-5763	A	-11526^	-12116	-5	31	

* : + for tension; - for compression
\+ : T for torsion; B for bending; A for axial; I for insignificant
^ : Assumed that load on leg 1 is equal to the measured load on leg 2
\# : E.D. for excessive distortion; L.L. for light loading (i.e., ratio of measured to yield or buckling load less than 10%.
% Difference = 100 x (Measured - Predicted) / Predicted

TABLE 7

COMPARISON OF MEASURED AND PREDICTED LOADS* IN MEMBERS JUST PRIOR TO FAILURE - TOWER 66

TOWER FAILED DUE TO WIND-ON-ICE LOAD

MEMBER		MEASURED LOAD (LBS)		TYPE OF PRE-DOMINANT LOAD IN MEMBER +	AVG. LOAD ON MEMBER (LBS)		%	RATIO OF MEASURED TO YIELD OR BUCKLING LOAD (%)	COMMENTS#
No.	TYPE	LEG 1	LEG 2		MEAS.	PRED.	DIFF.		
29-32	Horiz.	85	-94	T or B	-9	-180	--	--	E.D., L.L.
37-52	Horiz.	-1115	325	T or B	-790	-4595	--	--	E.D.
36-51	Horiz.	-2269	797	T or B	-1472	-4595	--	--	E.D.
38-44	Vert.	-7097	-7223	A	-14320	-21899	-35	50	
35-41	Vert.	-6022	-6931	A	-12953	-21889	-41	45	
50-56	Vert.	-8542	-6502	A	-15044	-21946	-31	41	
47-53	Vert.	-6291	-8666	A	-14957	-21946	-32	40	
48-54	Vert.	4514	2641	A	7155	5827	23	12	
49-55	Vert.	4810	4664	A	9474	5827	63	16	
45-54	Diag.	2696	2605	A	5301	9762	-46	31	
46-55	Diag.	2765	1798	A	4563	9762	-53	27	
46-56	Diag.	-4209	1040	T or B	-3169	-4	--	--	E.D.

* : + for tension; - for compression
\+ : T for torsion; B for bending; A for axial load.
\# : E.D. for excessive distortion; L.L. for light loading (i.e., ratio of measured to yield or buckling load less than 10%.
% Difference = 100 x (Measured - Predicted) / Predicted

TABLE 8

COMPARISON OF MEASURED AND PREDICTED LOADS* IN MEMBERS JUST PRIOR TO FAILURE - TOWER 67

TOWER FAILED DUE TO WIND-ON-ICE LOAD

MEMBER		MEASURED LOAD (LBS)		TYPE OF PRE-DOMINANT LOAD IN MEMBER +	AVG. LOAD ON MEMBER (LBS)		%	RATIO OF MEASURED TO YIELD OR BUCKLING LOAD (%)	COMMENTS#
No.	TYPE	LEG 1	LEG 2		MEAS.	PRED.	DIFF.		
29-32	Horiz.	70	-195	T or B	-125	-209	--	--	E.D.,L.L.
37-52	Horiz.	-3155	1157	T or B	-1998	-5431	--	--	E.D.
36-51	Horiz.	-3887	1784	T or B	-2102	-5431	--	--	E.D.
38-44	Vert.	-7793	-8443	A	-16236	-25486	-36	56	
35-41	Vert.	-8506	-8380	A	-16886	-25486	-34	58	
50-56	Vert.	-6621	-10726	A	-17347	-25519	-32	47	
47-53	Vert.	-9930	-9386	A	-19316	-25519	-24	52	
48-54	Vert.	5279	6327	A	11606	7534	54	20	
49-55	Vert.	2556	6243	A	8799	7534	17	15	
45-54	Diag.	3758	3727	A	7485	11534	-35	45	
46-55	Diag.	3373	3263	A	6636	11534	-74	40	
46-56	Diag.	-3189	5646	T or B	2457	-5	--	--	E.D.

* : + for tension; - for compression
\+ : T for torsion load; B for bending load; A for axial load
\# : E.D. for excessive distortion; L.L. for light loading (i.e., ratio of measured to yield or buckling load less than 10%.
% Difference = 100 x (Measured - Predicted) / Predicted

TABLE 9

STRUCTURAL PROPERTIES OF THE STRAIN GAUGED MEMBERS - TOWERS 66 & 67

MEMBER	YIELD CAPACITY IN TENSION (LBS)	BUCKLING CAPACITY IN COMPRESSION (LBS)	LENGTH (FT)	LONG LEG (IN)	SHORT LEG (IN)	THICK-NESS (IN)	WEIGHT (LBS/FT)	AREA (IN^2)
29-32	19200	2284	8.13	2	2	0.125	1.7	0.48
37-52	29200	5104	8	3	3	0.125	2.5	0.73
36-51	29200	5104	8	3	3	0.125	2.5	0.73
38-44	57600	28900	11.78	3	3	0.25	4.9	1.44
35-41	57600	28900	11.78	3	3	0.25	4.9	1.44
50-56	57600	37087	14.96	3	3	0.25	4.9	1.44
47-53	57600	37087	14.96	3	3	0.25	4.9	1.44
48-54	57600	37087	14.96	3	3	0.25	4.9	1.44
49-55	57600	37087	14.96	3	3	0.25	4.9	1.44
45-54	16800	1352	16.96	1.75	1.75	0.12	1.44	0.42
46-55	16800	1352	16.96	1.75	1.75	0.12	1.44	0.42
46-56	16800	1352	16.96	1.75	1.75	0.12	1.44	0.42

TABLE 10

STRUCTURAL PROPERTIES OF THE STRAIN GAUGED MEMBERS - TOWERS 65

MEMBER	YIELD CAPACITY IN TENSION (LBS)	BUCKLING CAPACITY IN COMPRESSION (LBS)	LENGTH (FT)	LONG LEG (IN)	SHORT LEG (IN)	THICK-NESS (IN)	WEIGHT (LBS/FT)	AREA (IN^2)
29-32	19200	2284	8.13	2	2	0.125	1.7	0.48
32-35	14400	835	17.33	1.5	1.5	0.125	1.23	0.36
35-38	26800	8408	10.83	2.75	2.75	0.125	2.3	0.67
38-44	57600	28910	11.78	3	3	0.25	4.9	1.44
30-31	19200	2306	8.1	2	2	0.125	1.65	0.48
50-56	57600	37095	14.95	3	3	0.25	4.9	1.44
36-37	26800	8408	10.83	2.75	2.75	0.125	2.3	0.67
36-51	29200	5104	8	3	3	0.125	2.5	0.73
47-53	57600	37095	14.95	3	3	0.25	4.9	1.44
37-43	57600	28910	11.78	3	3	0.25	4.9	1.44
39-53	14400	631	19.57	1.5	1.5	0.125	1.23	0.36
56-64	57600	36725	10.05	3	3	0.25	4.9	1.44
53-61	57600	36725	10.05	3	3	0.25	4.9	1.44
54-62	57600	36725	10.05	3	3	0.25	4.9	1.44
55-63	57600	36725	10.05	3	3	0.25	4.9	1.44

TABLE 11

LOAD TRANSFER INTO THE FOUNDATION AT TOWER NO. 67
LOAD STEP B-12 (MAXIMUM APPLIED WIND-ON-ICE LOADING)

TOWER(+) LEG No.	MEASURED* LOAD (kips)	PREDICTED** REACTION LOAD (kips)	
54 uplift	18	17.5	PLAN VIEW
55 uplift	15	17.5	55 56 x x Applied Horiz.
56 compression	19	25.5	----> Load at Top of
53 compression	19	25.5	x x Tower 54 53

Notes: (*) Based on strain gauge measurements
(**) Space frame with pin joints and fixed supports

(+) 2 rock anchors per tower leg

The loads were assessed based on the following structural geometry:

a) main legs are vertical
b) diagonal members are 30° to the vertical members.

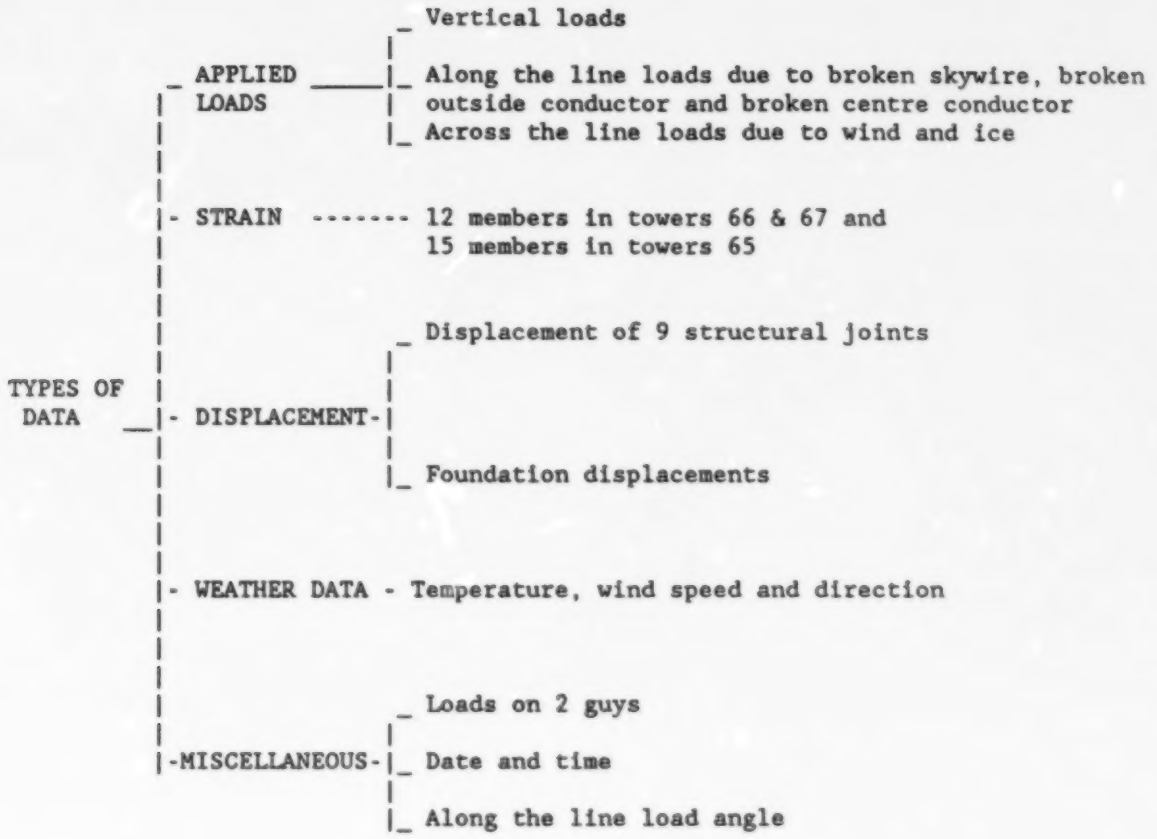
TYPES OF DATA
APPLIED LOADS
Vertical loads
Along the line loads due to broken skywire, broken outside conductor and broken centre conductor
Across the line loads due to wind and ice
STRAIN
12 members in towers 66 & 67 and 15 members in towers 65
DISPLACEMENT
Displacement of 9 structural joints
Foundation displacements
WEATHER DATA - Temperature, wind speed and direction
MISCELLANEOUS
Loads on 2 guys
Date and time
Along the line load angle

FIGURE 1 - SUMMARY OF THE DATA OBTAINED DURING TOWER TESTS

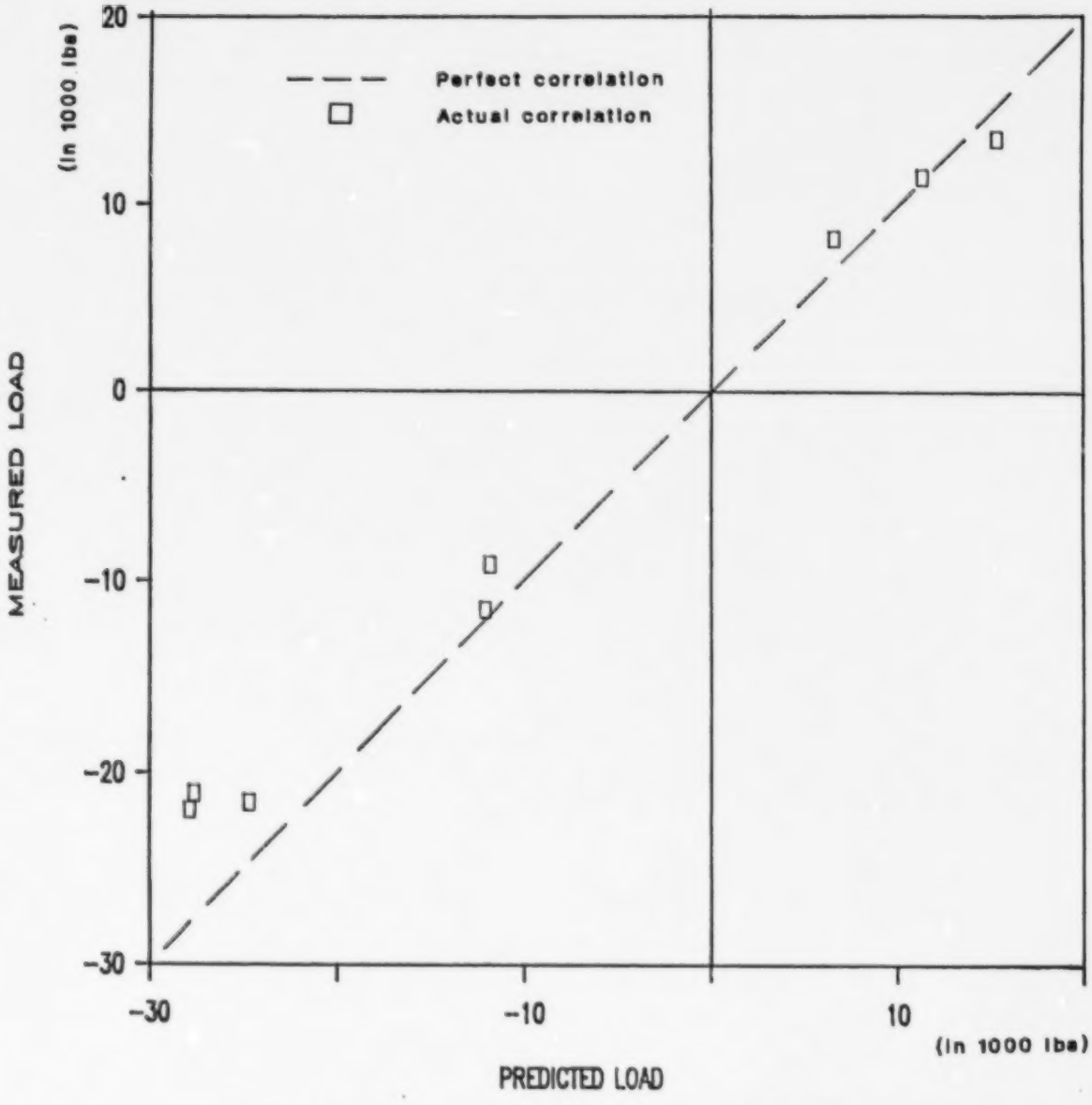

Figure 2 - Correlation of Measured and Predicted Loads in Tower Members (Tower 65)

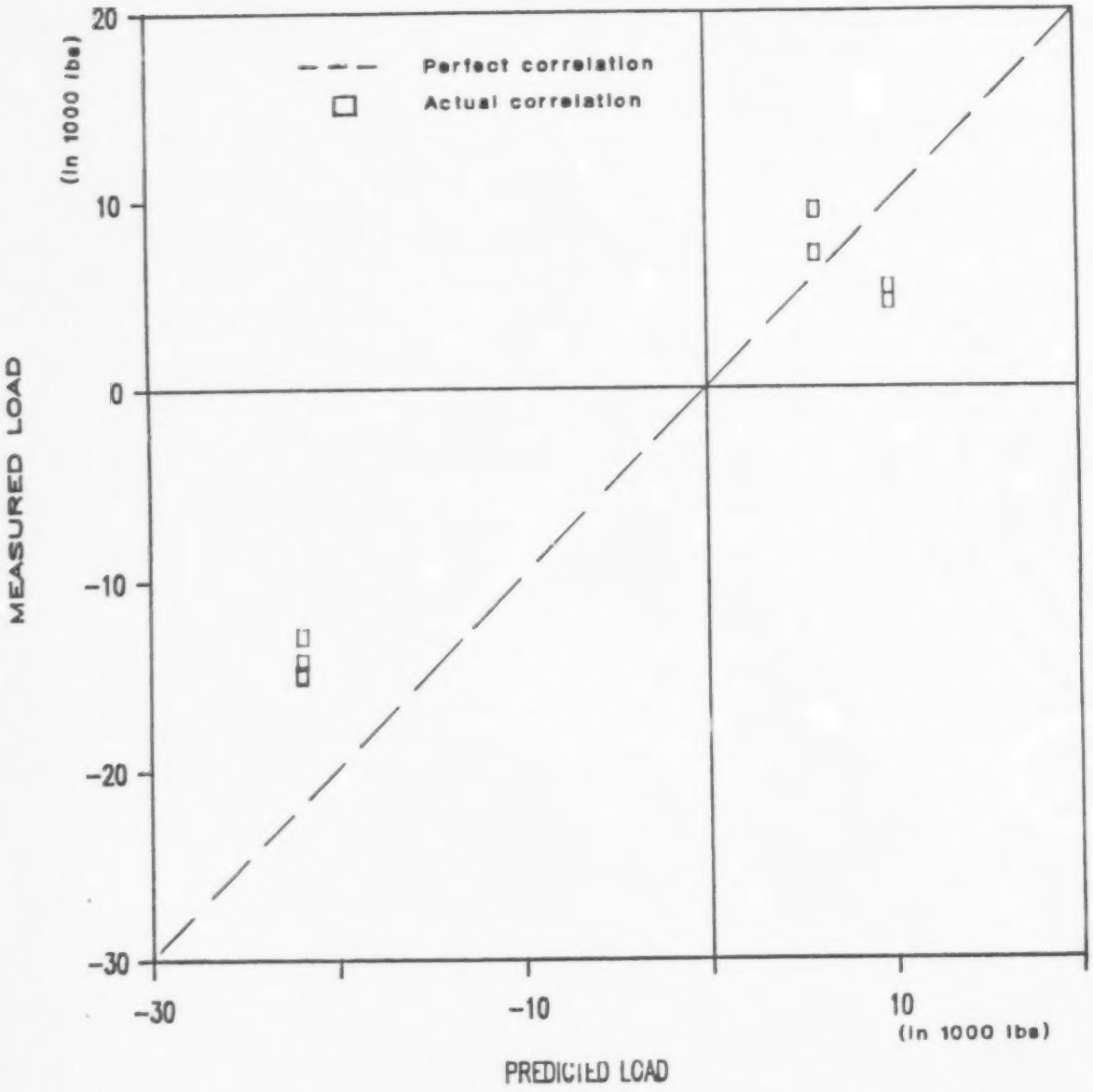

Figure 3 - Correlation of Measured and Predicted Loads in Tower Members (Tower 66)

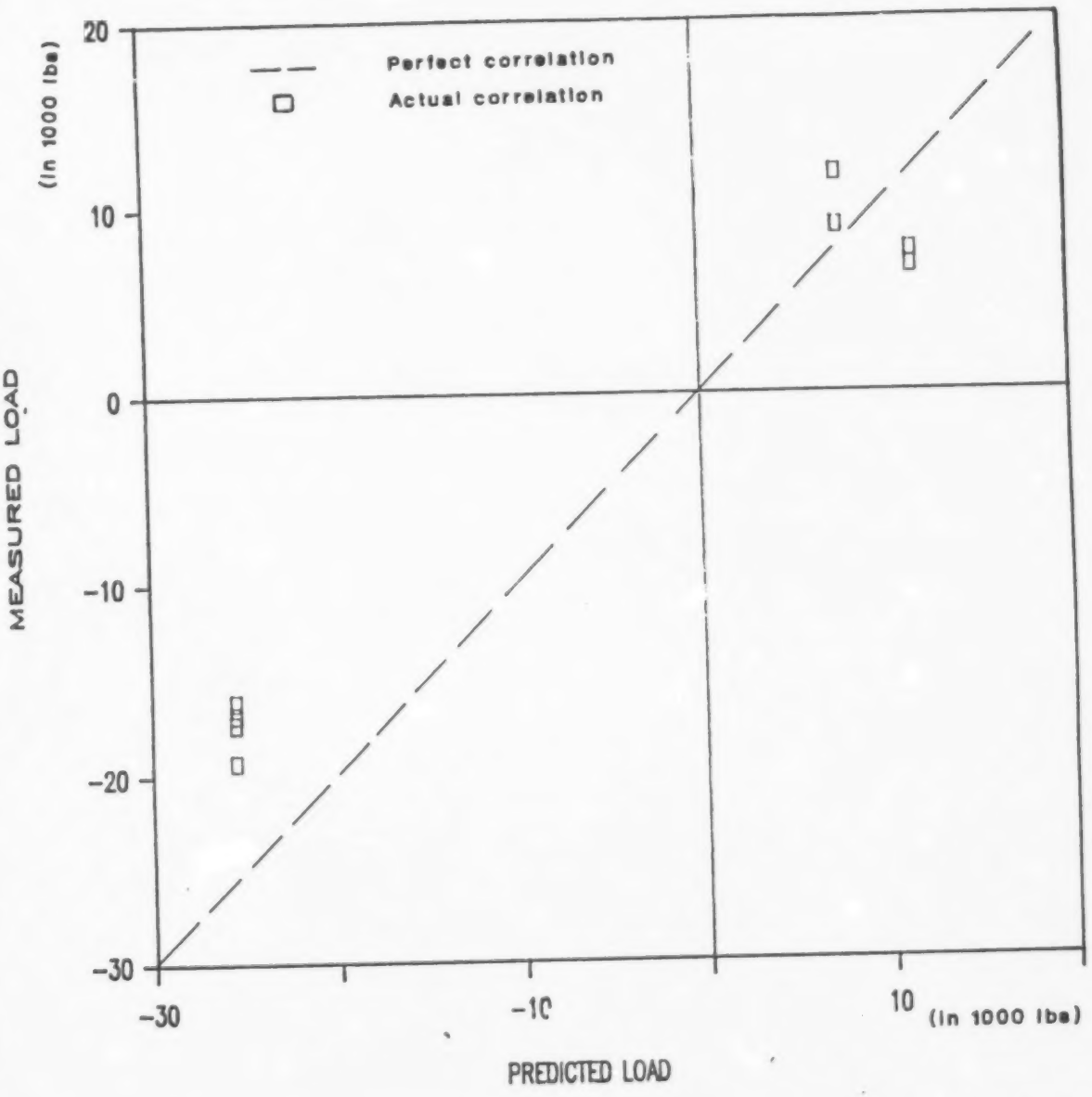

Figure 4 - Correlation of Measured and Predicted Loads in Tower Members (Tower 67)